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The ESD Colloquium Committee

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Attached are the extended abstracts received to date for the ESD Colloquium to be held on May 29 and 30, 2002. A proceeding of the complete papers are planned to be published in advance of the colloquium. We hope you find these abstracts to be a useful preview.

The ESD Colloquium Committee

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Managing the Development of Complex Engineering Systems

Thomas Allen and Ralph Katz

One of the more difficult problems facing developers of complex engineering systems stems from the degree of interdependence among subsystems and components that is inherent in such systems. This interdependence can be the result of physical interdependence, designed into the system architecture, or it can result from the interrelations among the tasks to be performed during development. (This task must be completed before that one is begun; the results of this test will determine how we accomplish that task, etc.). The handling of these interdependencies is one of the major (arguably *the* major) responsibilities of the project manager for the development. A simple one-sentence definition of a project manager's job is that, "A project manager manages interdependencies."

The difficulty of this assignment is the result of a number of factors. The first, of course, is the degree of interdependence designed into the architecture. Equally important is the way in which the overall development problem has been partitioned. The latter is only partially independent of the former. Project managers have some control over both of these factors but usually more over the second. A problem can often be partitioned in several ways and tasks assigned accordingly. Some partitionings will result in greater interdependence, others in less. Thus, the project manager can make his job easier or more difficult. Experienced project managers learn this and simplify their jobs by assigning tasks to minimize interdependencies among team members.

A second factor that affects the difficulty of the project manager's job lies in the nature of the technologies incorporated into or embodied in the system. If the system is based upon mature, stable technologies, the job is easier than when it is based upon dynamic, rapidly building technologies. In the latter case, there is, in addition to the need for coordination to manage interdependencies, a need to stay abreast of technological developments. In the former, the project manager can concentrate on the task of coordination without the distraction of worrying over changes in technology.

It is the need to accomplish both coordination and knowledge maintenance that led to the development of the product development matrix organization[1]. A major issue in the product development matrix is that of "balance" and the definition of responsibilities for project managers and departmental (or functional) management. One can argue (and many have) that the two sides of the matrix should be balanced. On the other hand, Clark and Fujimoto, (19--), in their study of the automobile industry show evidence for the effectiveness of what they label "heavyweight" project managers in effect, arguing for imbalance. While these views apparently conflict, it is possible that each may hold true for a particular type of project. When complexity (measured by the degree of interdependence among components or tasks) is high, the importance of project management increases and project managers may assume or be given greater authority.

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[1] No one knows, for certain, the origin of the matrix, but the author strongly suspects it was T. Wilson of Boeing who first organized it in the late 1950s.

When technologies are changing very rapidly, the departments responsible for these technologies increase in their importance and departmental management may assume or be given greater authority. The need for flexibility, pointed out by De Neufville, may also require greater influence from departments, since it is departmental research that is most likely to produce alternatives[2]. Other "ilities", for example maintainability may best be introduced through project management since project management provides the interface with other functions such as technical service and manufacturing. This paper will lay out a research project to test these hypotheses and will provide a limited preliminary test, using data, collected for another purpose on a large sample of projects from 10 U.S. organizations. Projects will be divided on the basis of size and estimated complexity and analyzed to see whether these differences are reflected in the degree of authority given to project and departmental management and whether there is any relation between the allocation of authority and project performance, as judged by senior management.

Preliminary results indicate that in the majority of the projects organizational influence and authority over technical decisions and were balanced between project and departmental management. At the same time, on more complex projects, performance is significantly higher when project managers have more influence over technical decisions. On smaller, less complex projects, performance is higher when project managers have more organizational “clout”.

The first of these results may seem surprising, since on large, complex projects one would doubt a project manager’s ability to understand all of the technologies that are involved and might devolve decision making to the departmental experts. Given the interdependencies that are present in such projects, such a strategy could miss the “big picture” and lead to decisions that while optimal at the technology or subsystem level are far from optimal at the system level. Project management, having a better understanding of the complexities at this level is therefore better suited to making technical decisions at the system level.

The second result is a little more difficult to understand and will merit further exploration. Additional comparisons on the basis of size and complexity will also be pursued.

[2] Project managers, and their teams, suffer an often fatal commitment to their existing design and tend to awaken to new alternatives far too late (Cf. Allen and Katz 19--; Allen 19--).

Learning From Organizational Experience

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MIT Engineering Systems Division Symposium, May, 2002

Extended Abstract

Learning-in-action, the cyclical interplay of thinking and doing, is increasingly important for organizations as environments and required capabilities become more complex and interdependent. Organizational learning involves both a desire to learn and supportive structures and mechanisms. We draw upon three case studies from the nuclear power and chemical industries to illustrate a four-stage model of organizational learning. In the first or "local" stage, knowledge is based primarily on the experience and skill of individuals. Learning is decentralized, closely tied to work tasks, and adaptive to performance outcomes. In the second or "control" stage, there is an emphasis on formalization and standardization through compliance with rules. Knowledge is organized in terms of disciplinary expertise. Learning is understood as a set of routines for training, performance feedback, statistical process control, after action review, procedure revision, and so forth. In the third or "open" stage, organizations recognize that routines cannot be written for all activities and all contingencies and that rapidly changing demands require flexibility, acknowledgement of doubt, and broad participation in learning. The open stage is based on attitudes and cultural values of involvement, sharing, and mutual respect, which provides the sense of psychological safety needed to explore and discover novel ideas and approaches. However, regardless of motivation, the structures and skills needed for systematic inquiry and systems thinking develop gradually in the final, "deep learning," stage.

Conceptually, the four stages differ on whether learning is primarily single-loop or double-loop, i.e., whether the organization can surface and challenge the assumptions and mental models underlying behavior, and whether learning is relatively improvised or structured. The local stage is single-loop and improvised; the control stage is similar in using single-loop learning to modify behavior without addressing underlying mental models, but it uses structured roles and processes to formalize and disseminate learning. The open stage begins to use double-loop learning to rethink basic assumptions and mental models, but in an improvised way. The deep learning stage adds structure and skilled inquiry to enhance organizational learning. Many organizations become locked into the control stage because the next stage requires both challenging deeply-held assumptions and giving up some of the perceived control that has been a strength of the organization.

The three case studies illustrate how organizations learn differently from experience, the details of learning practices, and the nature of stage transitions among learning practices. The first case illustrates the transition from local to controlled learning at a nuclear power plant. The plant conducted a problem investigation of a serious injury to a maintenance worker. The investigation process was relatively new, and intended to find and fix

problems of any sort. The investigation concluded that the worker had failed to pay attention and follow the accident prevention manual. Recommended corrective actions were directed at strengthening awareness and compliance with rules.

The second case illustrates the transition from the control stage to the open stage at a different nuclear power plant. At this plant, the control orientation had become so extreme that workers who raised safety concerns felt intimidated by management. Management was convinced that cost reductions were not eroding safety margins and that concerns from employees and regulators were misdirected. Eventually, regulators forced the plant to remain shut down until management could demonstrate a "safety conscious work environment" in which employees would feel safe raising concerns and management would act appropriately to evaluate and address concerns. The shift to an open learning environment took years of effort, changes in management, training in new ways of thinking and acting, development of trust and broad participation, and new structures to measure and support safety culture.

The final case illustrates the transition to deep learning at a chemical plant. New plant management adopted a highly sophisticated and labor intensive problem investigation process as a way to improve plant performance and gain deeper understanding of technical and human issues at the plant. We illustrate this learning process in the analysis of a major fire. The investigation appears on the surface to be the introduction of new investigation and analysis techniques, but upon deeper reflection it represents a negotiated interaction among managers and workers, and among multiple worker groups, to achieve a new relationship of openness and collaborative engagement. The collective analysis of factual details (with a disciplined logic that identified gaps) helped to drive a systemic understanding. Tools such as cause-effect diagrams were boundary objects negotiated by the investigation team in a process of knowing that helped surface previously unarticulated mental models of the work environment, compare them, and arrive at new, shared views. Some of the learning was articulated in the written report, another boundary object negotiated between the team and managers that initiates corrective actions and feeds databases, but much remained unwritten (although discussed as part of the reporting out process).

The Impact of Instability on Complex Social and Technical Systems

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Submission for presentation to MIT's Engineering Systems Division Internal Symposium February 2002

Introduction

Instability is a pervasive phenomenon that has deep implications for virtually all complex social and technical systems.

In engineering, the identification and mitigation of various types of technical instabilities is a well developed practice. This is a key focus, for example, of engineers concerned about the prevention of potentially destabilizing vibration in the frame of an aircraft or the elimination of potentially destabilizing bugs in a software program. However, to nature of instability in complex social and technical systems is relatively unstudied and not well understood.

In this paper, we present a conceptual framework for understanding instability in socio-technical systems. We then illustrate key concepts with data from the aerospace industry. Drawing on two data sets, we trace the impacts of three types of instability – technological, organizational and economic instability – on aerospace programs and production operations.

Consider the case of the F-22 program, which can be understood as a complex engineering design and production system. Economic instability is reflected in several successive budget cuts – some small and some substantial – that took place since the inception of the program. This has forced the development of more than 20 program master plans, with far-ranging ripple effects on the prime contractors, employees, suppliers, communities and other stakeholders. Technological instability is particularly evident in the avionics, which were first designed at a time when the fastest available computer chip was a 386 micro-processor. Each major advance in computer technology has forced complex sets of choices around what to re-design and what to functionality to leave unchanged, using the older technologies. Organizational instability is reflected in the merger of Lockheed, Martin Marietta, and General Dynamics into Lockheed Martin, as well as countless organizational initiatives, restructurings, partnerships, acquisitions, and leadership transitions. Despite these significant instabilities, the requirement to develop and deliver a complex, advanced aircraft system never wavered.

Not only must organizations develop and deliver complex systems while confronting the challenges of instability, they often are called on to simultaneously work to improve their own organizational productivity through activities such as Lean and Six-Sigma. A key statistical process control (SPC) principle revolves around the importance of stability (or at least reduced variability) as a pre-condition for improvement efforts. Most lean implementation frameworks urge the establishment of stability prior to the implementation of systems for "flow" and "pull." A deeper understanding of the nature of instability promises useful insights into how to achieve this most important reciprocal condition – stability.

Defining Instability

We define instability as a dynamic pattern of stimulus and response in which events become successively less predictable or controllable.

Classically, instability in physical systems is defined as a perturbation that is amplified by feedback in a divergent process – resulting in increased variability. In the context of many complex social and technical systems, there may be many perturbations, many related and unrelated responses and great difficulty distinguishing superficial symptoms from underlying sources of instability.

Note that stability does not necessarily mean the absence of perturbations or new stimulus. It is just a state where responses to perturbations do not induce unpredictable or uncontrollable outcomes.

Emerging Principles

The following principles have been developed on an inductive basis – emerging from the data analysis and from underlying concepts:

Single versus multiple sources of Instability: Complex socio-technical systems may be thought of as multivariate dynamic systems. As such, attempts to mitigate instabilities by focusing on one variable may actually induce more instability.

Time and Instability: Instability is a longitudinal dynamic phenomenon in which mitigation efforts must consider what can be termed the frequencies and harmonics of the underlying forcing functions, as well as the damping functions if they are to be successful. Practitioners should be wary of "one-shot" interventions.

Systems and Sub-Systems: Efforts to mitigate instability at a "sub-system" level will have limited impact when the source(s) of instability are at the level of the larger system.

Stakeholders: The impact of instability varies across stakeholders, requiring multiple stakeholder involvement in the mitigation response (corollary to the first principle)

Buffers and Root Causes: Common responses to instability involve attempts to create buffers that shield social and technical systems from the effects of instability, but these same buffers obscure data essential to understanding root causes (corollary to the second principle)

Illustrative Data

To illustrate some of the dynamics associated with instability, we present findings from two separate lines of research – one focusing on instability at what can be termed the program level instability and one on what is termed instability at the facility level. Both studies are focused on the U.S. aerospace industry. At the outset a few cautions are needed. First, the focus on aerospace means that the findings may or may not be fully generalizable to other sectors of the economy. Second, each of the studies involves cross-sectional survey research, combined with some longitudinal case study research – which will only partly capture important longitudinal aspects of instability. In this regard, the research should be treated as illustrative rather than confirmatory.

Among the key findings from the research on aerospace program instability are the following:

- Instability has a direct and negative effect on program cost, profitability, and duration.
- Multiple sources of instability (requirements, budget and technical) contribute roughly equally to the negative outcomes.
- Staff turnover in key roles correlated with instability, undermining remediation efforts and program performance at the time when instability is high.
- Implementation of cross-functional teams and other selected workplace innovations helped mitigate instability.

Among key findings from research on instability at the aerospace facility level are the following:

- Instability has a direct and negative effect on economic performance, skill development, employment and other factors
- Facilities report a wide range of sources of instability – with preliminary evidence for very different effects associated with economic, technological and organizational types of instability
- In implementing systems change initiatives, there is preliminary evidence for what has been termed a "golden middle" range of sufficient instability to unfreeze social relations, but not so much instability as to polarize stakeholder

Conclusions

This has been a preliminary exploration of the concept of instability. In complex social and technical systems, instability is both all pervasive and highly problematic. We have seen how narrowly focused responses to instability can actually increase, rather than mitigate the problem. As well, buffers designed to protect against instability can hamper understanding of root causes. While there are many negative impacts associated with instability, it can also serve a beneficial unfreezing role – in moderation. Ultimately, a deeper appreciation of instability enables a more effective focus on creating stability, which is the foundation for continuous improvement in social and technical systems.

Architecting/Configuring/Designing Engineering Systems Using Real Options

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MIT Engineering Systems Symposium
On the Intellectual Foundations of Engineering Systems
May, 2002

Extended Abstract

All of us concerned with engineering systems face a common fundamental problem. It is: How do we design these systems to perform well in a constantly evolving and thus risky context? As professionals concerned with the system (rather than its individual pieces) the design issues of course predominantly relate to the overall configuration, the architecture of the system.

Learning how to define the appropriate architecture, to configure engineering systems optimally, should be a central, and indeed an urgent task for all of us. At present we tend to do it suboptimally, perhaps even badly. As a colleague in this symposium suggests:

> "In traditional space systems conceptual design, point designs are chosen early to pursue. This has the benefit of jump-starting downstream design efforts, but has severe detriments in terms of sub-optimization and the cost of redesign." (Hastings et al.)

How do we configure computer systems, manufacturing plants, power grids, satellite arrays and other systems to evolve optimally in the uncertain environment defined by technological shifts, changes in industry structure and market fluctuations? In short, how do we design in the right kinds and amounts of flexibility into engineering systems? How do we guarantee that our systems are well positioned to take advantage of new opportunities, yet insured against poor performance in changed circumstances? If we could establish a methodology for determining the appropriate system architecture, we might well avoid the "severe detriments" mentioned by Hastings, and achieve significant gains.

The essential design difficulty is that, as other colleagues at this symposium indicate:

> "A system… is not a static design---it is a dynamic process that is continually adapting to achieve its goals and to react to changes in itself and in the environment." (Leveson)

We must, therefore learn how to explore the:

> "Tradeoffs between performance, cost, risk and schedule…during architecting and design of complex engineering systems." (de Weck et al.)

We do yet not know how to define, in any rigorous way, appropriately flexible system architectures. We can build in reliability. We can design for reasonable performance over a wide range of situations. However, we do not have a consistent engineering

approach to the general problem. Our schemes for measuring performance do not provide means to evaluate contingency plans. Until we develop appropriate ways to value the flexibility that we can build into our systems, we can neither make informed decisions about flexibility nor design the systems for optimal performance.

Simulation is almost certainly likely to be an essential tool to help us explore these issues. A broad range of new capabilities enables us to use this approach in ways previously unaffordable. As another colleague points out:

> "A new generation of stochastic simulation tools capable of exploring risk vs. efficiency tradeoffs in large-scale…systems…is now evolving." (Marks)

We will need to place such tools within a larger conceptual context. This is likely to use some form of construct that defines an optimum portfolio of system capabilities or assets. It will thus probably borrow heavily from recent developments in economics in this area. Colleagues within the Engineering Systems Division are already working on this approach. For example:

> "We have been exploring a methodology for concurrently evaluating uncertainties embedded in potential architectures and utilizing this information in the upstream conceptual design trade-offs. This methodology relies on the use of portfolio theory and the analogy that a trade space of architectures can be modeled as a marketplace of potential assets from which efficient portfolios can be created." (Hastings et al)

This paper explores how we might collectively approach this fundamental issue of designing the architecture of engineering systems. It proposes the possibility of a coherent approach to the design of flexible engineering systems that can evolve optimally to meet new challenges and opportunities.

It suggests that the methods of "options analysis"-- that have revolutionized thinking about investments -- can provide a conceptual basis for defining optimal configurations – much as Baldwin and Clark (2000) have proposed. The fundamental element of options analysis is indeed the determination of the value of flexibility. This approach defines the value of the "options", of the design elements that will permit system designers and managers to evolve their system gracefully over time as new opportunities and risks unfold.

When we can satisfactorily measure the value of flexibility, we will be able to determine the optimal kinds and amounts to incorporate into the system architecture. We will be able to determine, for example, the extent to which a more modular system (providing flexibility) is appropriate for the particular kinds of risks and opportunities we might anticipate.

The transposition of options analysis into the engineering context, into what is known as "real options," is not direct. Experts in finance have proposed possible approaches (see for example Brennan and Trigeorgis, Trigeorgis), but these do not seem adequate. The issue in this regard is that many of the assumptions central to the options analysis in the financial context do not apply to engineering systems. Specifically, with regard to engineering systems:

- Historical data on the volatility of the risks are generally unavailable;
- Decision points at which the exercise price of the "real option" is known may also be unavailable; and
- The risks are unlikely to evolve as Brownian processes but, on the contrary, are likely to change markedly even over a short time (in terms of an engineering system), for example as when market responses to new products become known.

An extended program of research is needed to create appropriate procedures for appropriately applying real options analysis to engineering systems. We need, through theoretical analysis and applications to numerous cases, to adapt the financial methods of options analysis to the reality of engineering systems. If successful, the resulting concepts and procedures could fundamentally alter the way we think about engineering systems design. The resulting methodology for defining system architecture could provide a core methodology for engineering systems analysis.

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Isoperformance:
A System Design and Evaluation Methodology

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(1) Abstract

Tradeoffs between performance, cost, risk and schedule frequently arise during architecting and design of complex engineering systems. Many such systems interact with human operators whose performance and abilities have been traditionally investigated in applied psychology and human factors engineering. Isoperformance is presented as a unifying methodology that can quantify and visualize the tradeoffs between determinants (independent design variables) of a known or desired outcome in this context. For deterministic systems the multivariable performance invariant contours can be computed using sensitivity analysis and contour following algorithms, provided that a mathematical system model of appropriate fidelity exists. In the case of stochastic systems the isoperformance curves can be obtained via omega-squared analysis, given a statistically representative data set. Once isoperformance curves have been obtained, they are useful in extracting a set of performance invariant solutions. Applying additional objectives, other than performance, can then lead to a set of pareto-optimal designs. Specific examples from opto-mechanical systems design and human factors engineering are presented.

Terminology: We use the word *isoperformance* by itself as shorthand for *the isoperformance approach*. This is a methodology for obtaining a performance invariant set, or a set of performance invariant curves (2D) or surfaces (>2D) given a data-analytic (stochastic) or deterministic model.

(2) Introduction

Isoperformance is based on the idea of holding a functional quantity f deemed to be representative of a system's "performance" constant and plotting the contours of equal performance on a two-dimensional graph. The ordinate and abscissa each represent independent variables x_1, x_2 and the contours, $f = f_o$, indicate the function values of a bivariate function:

$$x_1, x_2 \mapsto f\left(x_1, x_2\right) \tag{0.1}$$

Thus, one may represent the relationship between two variables (determinants) that together produce a constant effect [3]. In such a case both abscissa and ordinate represent determinants. An example of such a relationship that is common in meteorology is a pressure chart, where the contours represent the isobars, i.e. the contours of "equal" pressure at a given time and altitude, see Figure 1.

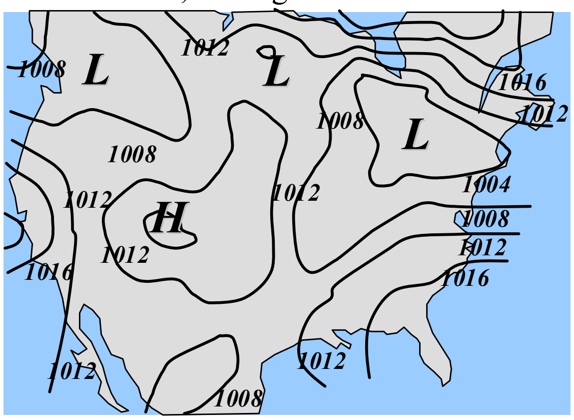

Figure 1: Sea Level Pressure [mbar] Chart: 1600 Z, Tue 9 May 2000. Here x_1 is geographic longitude, x_2 is geographic latitude and f is atmospheric pressure [1].

In this paper we are particularly interested in contours that arise, when the function f represents the performance of a system in a socio-technical context. Thus, f could represent the pointing performance of a space telescope, average gas mileage of a vehicle, total output of a power grid or the aptitude of humans as measured by some objective criterion. In economics, relationships of this type are usually called indifference curves [3]. In sensory psychology and physiology, they are often called isofrequency, isochronal or isoelectric curves or contours. These terms all share the prefix iso-, which means "same" . These contours are of value since they show the loci of "performance invariant" points in the x_1, x_2-space.

In the more general case we can be interested in multiple performance functions, whose values are determined by more than two variables. This can be expressed mathematically as:

$$x_1, x_2, \ldots, x_n \mapsto F = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_m \end{bmatrix} = \begin{bmatrix} f_1(x_1, x_2, \ldots, x_n) \\ f_2(x_1, x_2, \ldots, x_n) \\ \vdots \\ f_m(x_1, x_2, \ldots, x_n) \end{bmatrix} = J(x) \tag{0.2}$$

Thus, this paper presents an approach to finding a performance-invariant set **I**, where each member of the set produces the same response as the other member. The system response, however, is usually achieved by placing the burden on a different part of the system.

(3) Sample Results

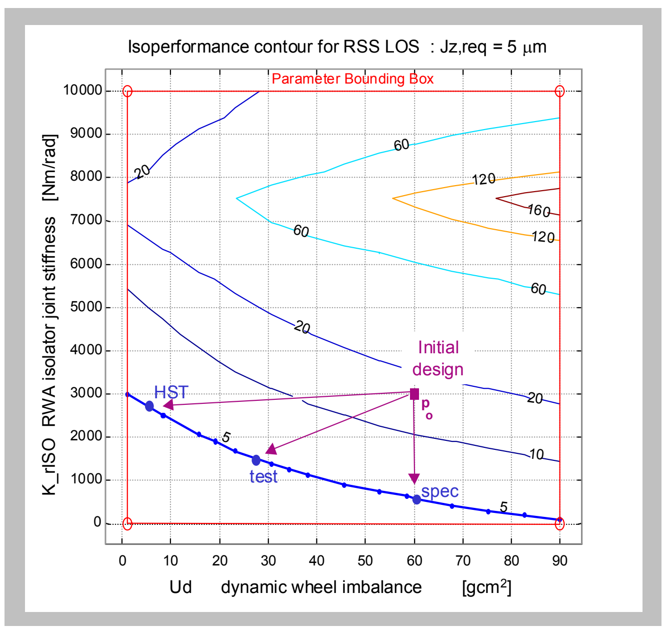

Figure 2: Bivariate isoperformance contours: Spacecraft design example, where the performance is the root-mean-square (RSS) line-of-sight (LOS) pointing performance of the satellite and a pointing level of 5 m (on the focal plane) is required. The initial design p_o does not meet the requirement and the isoperformance contour can be intercepted by a combination of changes. In this example the changes include diminishing the reaction wheel imbalance U_d and softening the isolator stiffness $K_{\_rISO}$.

Additional examples for multivariable isoperformance sets, and stochastic examples from human factors engineering will be included in the paper. A general approach for obtaining isoperformance solutions is shown below:

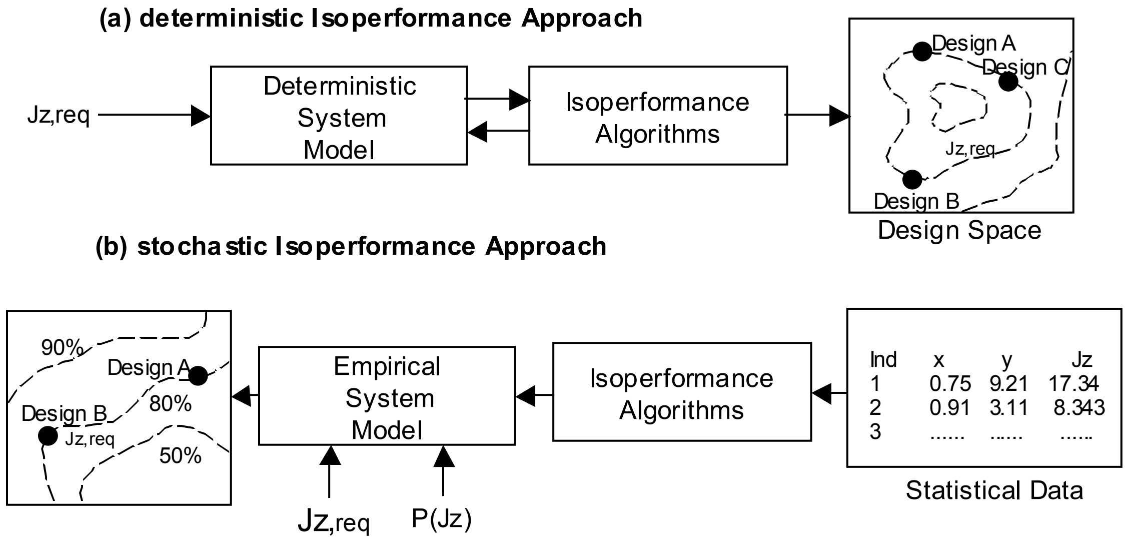

Figure 3: Deterministic and stochastic Isoperformance approaches. In the deterministic approach a mathematical system model exists and the isoperformance algorithms extract the performance invariant set at performance level Jz,req. The stochastic approach begins with a statistical data set from a population of "individuals" that exhibit certain attributes x_i and responses J_z. The isoperformance algorithms use this data set to create an empirical system model, from which isoperformance contours are extracted.

(4) Significance of Isoperformance for Engineering Systems

It is often true that traditional engineering education and practice makes heavy use of system optimization. Optimization is, of course, an important method and spawns a number of algorithms (numerical gradient search, heuristic techniques like genetic algorithms and simulated annealing) designed to maximize or minimize certain system responses. In reality, however, the notion of optimality for large, complex engineering systems is somewhat ill defined. In the case of multiple objectives we can consider pareto-optimality [4].

This paper argues that traditional optimization of system performance is not the only reasonable approach in the design of engineering systems. Isoperformance does not seek the extrema of system performance, but enforces that the system meet pre-determined performance goals (=requirements) subject to a numerical tolerance □. This is achieved by casting the system responses as equality constraints $J(x)=J_{req}$. This insures that the system is neither over nor under-designed. What can be gained by this approach?

There are three benefits for engineered systems that result from this approach:

(1) By not simply performing system optimization based on a mathematical system model, the entire design space is explored more fully.

(2) Designs that are found, within the performance invariant set, such that the burden for achieving the system response is well "balanced" or evenly distributed in the system.

(3) Performance as “currency”. The fact that the system is performance sub-optimal allows considering the difference between the “optimal” performance and the required performance along the isoperformance contours as an abstract resource. This performance margin can be viewed as a design “currency” that can be invested in different ways: making the system more affordable to implement, more robust or flexible, easier to upgrade in the future … This is the connection between system performance, optimization and the Illities.

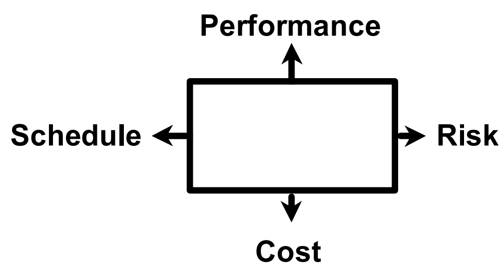

Figure 4: Tensions during systems architecting and design, Reference: [2], page 83, Figure 5.1. Traditional System performance optimization pulls strongly in the performance direction at the expense of the other directions. Isoperformance fixes the amount of performance at an acceptable level and trades off the other directions with respect to each other. The paper will argue that other tradeoff-dimensions are present, namely the downstream influences (manufacturability, flexibility, robustness etc…)

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Incorporating Uncertainty into Conceptual Design for Space System Architectures

Daniel Hastings, Myles Walton, and Annalisa Weigel

Space system architectures traditionally define “rocket science”. However, while most often these architectures, once constructed, deliver excellent performance, it is extremely rare that they deliver the initially promised performance on the initially proposed cost and schedule. There are several reasons for this but a large amount of the blame lies in the fact that there is a little understanding of how to incorporate uncertainty into the design process in a way allows decision makers to systematically take uncertainty into account.

The development of space systems is subject to not only cost, technical and market uncertainties, but also to uncertainties from the policy domain. This paper introduces an approach to quantify and compare space system architectures under uncertainty, with emphasis on policy uncertainty as well as technical uncertainty. Two key hypotheses are developed and explored in this paper. The first is that the cost of policy can be quantified through technical analysis of space system architectures under varying policies and the second is that uncertainties of space system architectures can be quantified and managed effectively by carrying portfolios of architectures, rather than any single architecture.

Through interviews with space system architects, current methods of uncertainty analysis were collected, while at the same time interviews were conducted with top-level management and policy domain experts to uncover some of the policy uncertainties that have traditionally had considerable impact on space systems development. Using the information collected, an approach is developed that can be used in early conceptual design for quantifying the effects of policy and other uncertainties on the selection of space systems architecture.

Uncertainty analysis in conceptual design has traditionally focused on understanding the cost and, to some degree, technical uncertainty. Cost uncertainty is typically calculated through the use of regression errors associated with cost models that are used in early conceptual design and are based on historical missions of similar characteristics. Technical uncertainty in early conceptual design has historically been incorporated in two ways. The first is through the use of technology readiness levels at the subsystem or architecture levels. These technology readiness levels (TRL) are used to associate technical maturity with historical deviations of predictions of cost and schedule on the operational deployment of the technology. This is as crude as then carrying a percentage uncertainty associated with each TRL. The second method of technical uncertainty analysis is to identify major sources of risk and to develop probabilistic risk assessment based on individual scenarios using expert advise on probabilities and outcomes. More often than not, uncertainties arising from policy are not considered in the early conceptual design, or when they are, there is no method for quantifying the effect on the architectures and including that information in the conceptual design decisions. This paper provides a unifying framework for uncertainty analysis, but also a method for communicating the effects of policy between the political and architecture domain.

Enabling this approach is simulation modeling of space system architectures that are of interest in the design trade space. Using computer models to quantify the performance and cost characteristics, tradespaces of architectural characteristics can be developed and analyzed. These tradespaces are then searched to find the pareto optimal fronts in the space based on some criteria (e.g. minimum cost, maximum function per cost etc.)The simulation also allows for the propagation of uncertainty in various architectural characteristics and an understanding of how those uncertainties propagate to system evaluation criteria.

The first step in the proposed approach is an analysis of the trade space of potential architectures. This analysis includes bounding the problem in terms of the architectural concepts that will be evaluated and the bounding of the policy uncertainties and scenarios that will be investigated in addition to the other uncertainties that have significant impact on architectural evaluation. The second step is to adjust the models to reflect the effects of these uncertainties of interest on the simulation. The third step is to quantify the impact of the uncertainties on the system evaluation criteria for each architecture of interest. Finally, we incorporate portfolio theory as an approach to manage uncertainty effectively.

To illustrate the approach in practice, we use several case studies. We examine the effect of the cost of US launch policy on space launch architectures. We examine the effect of various types of uncertainty on a military space based radar mission. We compare and contrast the choices of architectures on the basis of performance and on the basis of minimizing uncertainty. Finally we also consider a commercial case of a broadband space architecture and consider the choice of architectural portfolios when uncertainty is minimized versus other choices that may be made.

A New Control-Based Model of Accidents

Nancy G. Leveson

Accident models underlie all hazard analysis, accident investigation, fault tolerance and safety design, and risk assessment techniques. Virtually all current safety engineering and risk assessment techniques are based on an underlying model that views accidents in terms of a forward chain of events over time. The chain may be branching (e.g., fault trees or event trees) or there may be parallel chains, but the relationship is almost always a direct, linear one and the events considered involve some type of component failure, human error, or energy-related event. It is difficult or impossible to incorporate into such models factors other than simple failure events and conditions, such as structural deficiencies in the organization, factors related to the safety culture in the industry, management deficiencies, cognitively complex human decision-making involving complex feedback relationships and interactions, and adaptation and degeneration of safety defenses over time.

In addition, chain of events models work best for component failure accidents, where one or several components fail, leading to a system failure or hazard. The extraordinary interactive complexity of the systems we are trying to build as well as the introduction of new technology, particularly digital technology, have led to a new type of accident, called "system accidents" by Perrow, that arises in the interactions among components (electromechanical, digital, and human) rather than simply the failure of individual components. While better engineering techniques, often involving redundancy, are reducing accidents related to hardware failure, system accidents are increasing in importance and will require new prevention approaches.

In this paper, a new model of accidents is proposed based on control theory. Instead of specifying the causal factors of accidents in terms of failure events and attempting to prevent those events by using various types of redundancy, accidents are seen as resulting from flawed processes operating within the overall socio-technical system. A significant difference from other models is the inclusion of the social system in the model. This feature allows considering such factors as the "safety culture" and management flaws in the investigation or prevention of accidents.

In the new model, systems are viewed as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control. Safety is an emergent property that must be controlled at each level of the socio-technical control structure by imposing the constraints necessary to limit the behavior of the process at the level below to safe changes and adaptations. Accidents result from inadequate control or enforcement of constraints on safety-related behavior. Accidents can be understood, therefore, in terms of why the controls that were in place did not prevent or detect maladaptive changes, that is, by identifying the safety constraints that were violated at each level of the socio-technical control structure as well as why they were inadequate or, if they were potentially adequate, why the system was unable to exert appropriate control over their enforcement. Thus, the most basic concept in the new model is not an event, but a constraint. As an example, the unsafe behavior (hazard) in the Challenger loss was the release of hot propellant gases from the field joint. The miscreant O-ring was used to control the hazard, i.e., its role was to seal a tiny gap in the field joint created by pressure at ignition. The design, in this case, did not effectively impose the required constraint on the propellant gas release. Starting from here, there are then several questions that need to be answered to understand why the accident occurred. Why was this particular design unsuccessful in imposing the constraint, why was it chosen (what was the decision process), why was the flaw not found during development, and was there a different design that might have been more successful. These questions and others consider the original design process.

It is also necessary to examine the contribution of the operations process. One constraint that was violated during operations was the requirement to correctly handle feedback about any potential violation of the safety design constraints, in this case, feedback during operations that the control by the O-rings of the release of hot propellant gases from the field joints was not adequately enforced by the design. There were several instances of feedback that was not adequately handled in this case, such as O-ring blowby and erosion during previous shuttle launches and feedback by engineers who were concerned about the behavior of the O-rings in cold weather. In addition, there was missing feedback about changes in the design and testing procedures during operations, such as the use of a new type of putty and the introduction of new O-ring leak checks without adequate verification that they satisfied system safety constraints on the field joints. As a final example, the control processes were flawed that ensured unresolved safety concerns were adequately considered before each flight, i.e., flight readiness reviews and other feedback channels to project management making flight decisions.

A system in this new model is not a static design---it is a dynamic process that is continually adapting to achieve its goals and to react to changes in itself and in the environment. The original design must not only enforce appropriate constraints on behavior to ensure safe operation, but the system must continue to operate safely as changes occur over time. The process leading to an accident (loss event) is described in terms of an adaptive feedback function that fails to maintain safety as performance changes over time to meet a complex set of organizational and individual goals and values. Preventing accidents is accomplished by ensuring that appropriate constraints are enforced, both in the system design and during operations and that the control structure (including the organizational culture and the management structure) enforces the appropriate set of goals and values.

The use of such a model provides a theoretical foundation for the introduction of unique new types of accident analysis, hazard analysis and risk assessment techniques, approaches to designing performance monitoring and safety metrics, and accident prevention approaches at all levels of the socio-technical control structure from the highest government and legal system levels down through the organizational levels to the lowest level technical design and operations.

STATUS: Using basic accident and system theory, I have identified a set of general factors that can be used to explain and prevent accidents using this new model. I've experimentally applied the factors to understand several past accidents, including the Ariane 5 loss, a Titan/Centaur/Milstar loss, and the accidental shootdown of two U.S. Blackhawk helicopters by friendly fire in the Iraqi no-fly-zone, and compared the results with those obtained by the official accident investigation board in each of these cases.

I am now starting to determine how the model and the identified general accident factors can be used to prevent accidents, not just explain those that have occurred, by using a model I created of the control software for an industrial robot. The robot is designed to service the thermal tiles on the space shuttle between flights. The result should be a new type of hazard analysis technique (very different from the traditional techniques such as fault tree analysis). This new hazard analysis technique can be partly automated, and automated assistance can be provided for the other parts that require human analysis. Finally, I have a Ph.D. student looking at the potential use of the model to define new types of risk assessment that work better for complex systems and include more factors than traditional Probabilistic Risk Assessment (PRA). I will be looking at how the results of the new hazard analysis technique can be used to identify important performance metrics that can identify a drift of the system and organization toward greater accident risk during use of the system (operations).

All of this is part of a book I am writing that is about one third finished. The completed parts include a description of the basic model and the analysis of the three accidents (to be finished in 2-3 weeks). The new hazard analysis technique is in development and the new risk assessment approaches are farthest off. The ESD symposium paper will describe the rationale for the model (why current models are not adequate), the new model, and the results of the evaluation using previous accidents (all of this is completed or very close to being complete). At the end, the paper will outline implications for the use of the model including potential new hazard analysis and risk assessment techniques and use to generate safety performance metrics.

Complexity -- the State of the Art

Seth Lloyd

Abstract: This talk provides a review of work on the sciences of complexity. Topics presented include complex adaptive systems, agent-based modeling, emergent behaviors, artificial life, genetic algorithms, cellular automata, econophysics, autocatalytic networks, origins of life, etc. Methods for the analysis and characterization of complexity will be presented with an emphasis on the successes, failures, and future prospects of these methods. The degree of overlap with engineering systems issues will be discussed.

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\noindent Frontiers of Complexity: The Search for Order in a Chaotic World

\noindent by Peter Coveney and Roger Highfield, Fawcett Columbine,
Ballentine Books, New York, 462 pages, \$27.50.

\bigskip\noindent Hidden Order: How Adaptation Builds Complexity

\noindent by John H. Holland, Helix Books, Addison-Wesley, Reading,
Massachusetts, 185 pages, \$24.00.

\bigskip\noindent Fire in the Mind: Science, Faith, and the Search for Order

\noindent by George Johnson, Alfred A. Knopf, New York, 379 pages, \$27.50.

\bigskip\noindent At Home in the Universe: The Search for the Laws of
Self-Organization and Complexity

\noindent by Stuart Kauffman, Oxford University Press, New York, Oxford,
321 pages, \$25.00.

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Complexity is complex. On this everyone agrees. The Fibonacci sequence appears in a pattern of sunflower seeds; corporate hierarchies of who pays or obeys follow the same mathematical rules as ecological hierarchies of who eats or is eaten; human beings and pygmy chimpanzees have a hard time with their in-laws. Complex systems share common patterns, as if an underlying order bound them together. But whether this underlying order admits systematic study, or whether complexity arises from a lawless variety that tolerates few generalizations, is open to debate. The four books reviewed here describe attempts to study complexity systematically and scientifically. Although they speak with different voices, the books' authors agree that the sciences of complexity are thriving. Other voices (such as that of John Horgan in these pages) raise a different argument: the sciences of complexity are, if not bogus, devoid of concrete results. Who is right?

The Latin {\it complector, complexus} comes from the Greek $\pi\lambda\epsilon'\kappa\omega$, to plait or twine. A complex system is woven out of many parts. The sciences of complexity try to understand the patterns of the weave. The orator Cicero used {\it complexus} to describe an intricate rhetorical argument, while the bawdy playwright Plautus preferred to use {\it complexus} to describe intertwined limbs in a sexual embrace. To make sense of the current debate on complexity, Plautus's meaning is more helpful.

The sciences of complexity promiscuously embrace almost every subject that calls itself science, and a few that do not. A search of the MIT library data base reveals `complexity' in anthropology, biology, chemistry, computer science, cosmology, dentistry, design, economics, ethnography, functional analysis, geology, historical studies, housing, immunology, information theory, Islamic architecture, Japanese calligraphy, knapsack problems, linguistics, material science, mathematics, music, numismatics, operations research, philosophy, physics, portfolio management, quantum computers, radiology, statistics, telecommunications, theology, ultrathin films, urban planning, vibrational failure, water pollution, wavelets, X-ray diffraction, ytterbium spectra, and zoology, to name but a few out of thousands of references. It is just not possible for the same mathematical techniques to apply rigourously to all these subjects: in some fields `scientific' approaches to the study of complexity are indeed devoid of concrete results. Like Don Juan, the sciences of complexity sometimes simply strike out.

In some fields, however, a systematic approach to studying complexity is not only successful, but is the only possible way to succeed. Just what does a scientific study of complex systems have to offer? Compared with conventional sciences, the sciences of complexity as detailed in the books under consideration emphasize distinctive methods and questions. 1) They focus on information: how do complex systems get information and what do they do with it? 2) They use detailed computer models for hypothesis testing and generation: how do computerized neurons behave when wired together in a chunk of artifical brain called a neural net? When artificial stock brokers buy and sell artificial stocks does the resulting market exhibit booms and busts? 3) They emphasize emergent properties: how do the laws of chemistry arise from the laws of physics, or the laws of biology from the laws of chemistry? In general, how do complex, specific laws arise from simple, generic ones? The techniques developed for studying complex systems are useful at the boundaries between conventional fields, where well-understood laws like chemical laws give rise to well-documented phenomena like life in a way that no one fully understands. Even when the parts of a system are perfectly understood, when woven together they can exhibit behavior that is too intricate and involved to be easily understood. In such cases, often the only recourse is to create an information-based model for the system and simulate it on a computer. For some fields, the systematic study of complexity is essential.

The goals of the sciences of complexity are hardly new. After all, Aristotle's {\it Physics} (from the Greek $\phi \upsilon\sigma\iota'\varsigma$, begetting or becoming) can be regarded as an abortive attempt to understand the laws of emergence. Montesquieu's {\it Spirit of the Laws} or Comte's {\it Positivism}, Poisson's probabilistic analyses of the fairness of trial by jury, as well as the sociological theorizing of Walras and Pareto, span two hundred years of attempts to create analogues of Newton's laws for complex social systems. What is new? The computer. In the last fifty years, the exponentially increasing ability of machines to process information has allowed the exploration of realms of complexity that were previously inaccessible.

Not that computers are so smart. It's just that human beings are relatively dumb, at least when it comes to performing mind-numbingly repetitive mathematical manipulations. In the past, to trace out the consequences of even the most over-simplified models for how proteins fold or how clouds form was virtually impossible. Now, however, the economist need not assume that agents are omniscient, that markets clear instantaneously, or that money is the only thing that matters. Though computerized models are still necessarily simplified, they can include much more detail than was previously possible.

These four books are full of examples of subjects where the sciences of complexity work, and work well. Trained as scientists, Peter Coveney and Roger Highfield demonstrated themselves to be a formidable writing duo with their previous book, {\it The Arrow of Time}. Their current book, {\it Frontiers of Complexity}, provides a lucid account of lines of research in which an emphasis on information and computation has yielded surprising and fascinating results. {\it Frontiers of Complexity} is a bestiary of complex systems, complete with color prints of artificial life forms. Packed with information, including an extensive bibliography and glossary, the book begins by introducing the reader to Alan Turing and John von Neumann, who can be thought of as the father and mother of the the modern digital computer (Turing provided an abstract blueprint for a computer: von Neumann joined Turing's blueprint with his own basic ideas and then labored to bring some of the first computing machines into the world). A section on the history of computation supplies the reader with a tool kit containing fundamental concepts of information and computation. The tools in the kit are easily grasped, and allow the reader to handle the dizzying array of results on neural nets, chaos theory, origins of life, quantum computers, brain imaging, etc., that follow. Each subject is clearly explained on its own, so that like any good bestiary, the book is perfect for browsing. (The downside of having stand-alone sections is that a topic can be introduced on one page, then reintroduced several pages later as if it were being met with for the first time.)

The book is particularly detailed on the subject of artificial life. In the 1950's, von Neumann analyzed the problem of self-reproducing organisms in the abstract, by investigating computerized organisms, or automata, that were capable of creating copies of themselves. He noted several features that a self-reproducing automaton must possess, all of which turned out to be features of living cells once DNA was identified as the genetic material. Contemporary offspring of von Neumann's idea exhibit a wide variety of `biological' behavior, including parasitism, immunity, and malignancy. Anyone whose computer has been infected by a virus has had first hand experience of artificial disease and the difficulty of killing off an artificial life form.

Although it surveys fewer subjects than {\it Frontiers of Complexity}, John Holland's {\it Hidden Order} provides a considerably deeper view into the possibility of automata behaving as if they were alive. One of the pioneers of the sciences of complexity was the Polish mathematician Stanislaw Ulam. Like von Neumann, Ulam contributed to many branches of mathematics, and invented the now ubiquitous Monte Carlo technique for simulating the behavior of complex systems by using random numbers or throws of the dice. Ulam collaborated with von Neumann in his artificial life project, and showed how automata could live out their artificial lives in an extended computerized world called a cellular automaton. {\it Hidden Order} is based on the Ulam memorial lectures delivered by Holland at the Santa Fe Institute. In it, Holland recapitulates some of his MacArthur award-winning work on genetic algorithms---computerized analogs of the processes of mutation and recombination that underlie biological evolution. Holland shows how computers can learn to cope with complexity by imitating how living creatures cope with their complex environments. He articulates clearly just how computer models can be used to study complex adaptive systems, and notes that mindless modeling accomplishes nothing unless it is supplemented with insight and reflection.\footnote{*}{Feynman noted that people who wish to analyse nature without using mathematics must settle for a reduced understanding: Holland introduces simple mathematical equations to illustrate his points. For the reader who is reasonably comfortable with the math learned in fifth grade, the equations should prove no obstacle, and they greatly increase the understanding of how artificial organisms adapt or fail to adapt to their environment. } A considerable part of the book is devoted to the description of an ambitious and as yet incomplete artificial ecosystem called Echo; some reader may find more compelling the brief section on the artificial stock exchange, created by Holland with economist Brian Arthur and physicist Richard Palmer along lines suggested in discussions with the Nobel laureates Kenneth Arrow (economics) and Phil Anderson (physics). In this electronic arena, mindless but greedy automata bid against eachother's strategies, producing speculative bubbles and crashes and other real-life phenomena that classical economics with its perfect markets has difficulty reproducing.

As the list of contributors to the artificial stock exchange indicates, the study of complex systems is fundamentally an interdisciplinary excercise: the underlying order in ecology can be compared with that in economics only by people who understand both. But research that weaves together ideas from many fields to try to solve a problem in a particular field is likely to face opposition from the workers in that field. The logic of academic turf battles demands that interlopers be challenged, just as do the logics of military battles, of challenges to the dominance hierarchy in primate groups, of presidential primaries, and of bacterial infections. Interdisciplinary work can be labelled `bogus' because it is wrong, or because it fails to address the prevailing dogma.

Life is by definition the provenance of biologists, who have painstakingly elucidated many of the chemical processes that underlie life as we know it. But life as we know it evolved from earlier life forms we don't know as much about. When it comes to the chemical processes that resulted in the first life on earth more than three million years ago (discounting for the moment the speculative theory that life was `seeded' from space), virtually nothing is known. Computer-based simulations of chemical reactions from which life might have arisen are currently being carried out by theoretical biologists, who are regarded with suspicion by some of their colleagues.

Stuart Kauffman, M.D. and MacArthur fellow, has been one of the most productive of theoretical biologists. He has followed up his more technical {\it The Origins of Order} with {\it At Home in the Universe}, an account of how life might have arisen from non-life and how complex order might have arisen not from chaos, but from the edge of chaos. At the conceptual center of {\it At Home in the Universe} lie Kauffman's simple and suggestive models. Particularly relevant to the origins of life is the notion of an `autocatalytic set,' an idea suggested by Melvin Calvin and explored independently by Otto R\"ossler, by Manfred Eigen, and by Kauffman. An autocatalytic set arises when a group of chemicals react with eachother to produce other chemicals that in turn encourage or catalyze the original reactions. Starting at almost negligible concentrations in a given volume, such a set of chemicals and reactions can by mutual catalytic encouragement rapidly come to dominate the volume. The set effectively reproduces itself and can evolve if it discovers new reactions and creates new products. Eventually, the story goes, the evolving set hits upon the chemical reactions that make up life.

This is potentially a convincing story, and lacks only a detailed analysis of the chemical kinetics to be confirmed not just as good science but as superb science (Eigen received a Nobel Prize in part for his work on hypercycles, autocatalytic sets involving RNA). Doyne Farmer, Norman Packard and Richard Bagley managed to program a Los Alamos computer with a simplified, artificial chemistry that exhibited autocatalytic sets; unfortunately, the actual chemical kinetics are too complicated to be analyzed even by the fastest computer available. If it is to be confirmed, the autocatalyic set hypothesis for the origins of life will have to await more powerful computers and more detailed chemical experiments.

The explanations of Kauffman's scientific work are concise and convincing. The prose that surrounds the explanations is less so. The chapter on autocatalytic sets, entitled `We the Expected,' begins with the sentence, `What raw day first saw life, raw life itself, pregnant with the future?' Even if autocatalytic sets turn out to be the correct model for the origins of life, they shouldn't be expected to answer such questions. Like Anglo-Saxon epic poets, Kauffman is fond of alliteration and internal rhyme: `Physics, cold in its calculus,' `coyote crafty across the ridgetop,' or `the fleeter-flying fly decreases the fitness of the frog.' Some may enjoy this wordplay, others may think of Beowulf on bad acid. Whoever reads {\it At Home in the Universe} for its account of Kauffman's insightful models of adaptation and self-organization will find that the scientific results speak for themselves.

The most remarkable and eloquent of these four books on the sciences of complexity is the only one not written by a scientist. George Johnson's {\it Fire in the Mind} examines not only How people search for order, but Why. No scientist could have written this insightful study. Scientists are usually too consumed with their own search for order to step back and ask, Why search? As to How, scientists answer with one voice: by Science! Scientists are people with an unquestioned faith in questioning everything. But this faith in reason and experiment is as important for science as faith in God is for religion. Both based on faith, science and religion ask many of the same questions. {\it Fire in the Mind} compares point by point the stories that science and religion tell of how the world began, what it is made of, where life came from, and what the future holds.

Taking the landscape of northern New Mexico as backdrop, Johnson fills his stage with scientists from the Santa Fe Institute, Indians from San Ildefonso pueblo, bomb makers from Los Alamos, and flagellants from the Catholic sect of Penitentes, and lets them speak. Of these, only the first group is not bound by vows of secrecy, and so says the most. Johnson's account of subjects such as artificial life and autocatalytic sets is the most incisive and readable of those in the books reviewed here. In addition, his taste for the mysterious has lead him to two quiet scientific success stories not reported in the books above: in the last two decades, scientists such as Charles Bennett at IBM, Wojciech Zurek at Los Alamos, and Carlton Caves at the University of New Mexico have revealed the pattern in which information is woven together with entropy in thermodynamics; over the same period, a number of scientists including Zurek and Murray Gell-Mann, Nobel laureate in Physics, have made great progress in showing how the concrete classical world we see around us is braided out of insubstantial quantum events. (Gell-Mann's intellectual autobiography {\it The Quark and the Jaguar} contains an engaging and incisive discussion of the sciences of complexity.) Like a magician conducting a master class, Johnson regales us with strange phenomena, then reveals them to be completely explicable.

His years as a science reporter for the New York Times have made him adept at succint explanation. But Johnson's desire not only to explain, but to understand the urge to explain, provides {\it Fire in the Mind} with its own fire. The book is at its most original and revealing where it discusses the social functions of knowledge and understanding. Johnson examines the ways in which three cultures, Indian, Spanish, and Anglo, overlap to shape northern New Mexican life,\footnote{*}{Anglo, short for anglo-saxon, means here neither Indian nor Spanish: to be Jewish in Santa Fe is still to be an Anglo.} and explores at length the problems faced by communities and by individuals who wish to preserve traditional knowledge that conflicts with contemporary culture or with scientific knowledge. In the end, the dominance of scientific knowledge, like that of pop culture, comes primarily from its drive to make itself accessible to everyone.

Scientific results are exactly those that can be reproduced in principle by anyone (or at any rate, anyone with a grant from the NIH). Science is by nature public. In the past decade, most major newspapers throughout the world have begun to publish weekly science sections. The books reviewed here owe their lush production values and large press runs, if not their very existence, to the well-deserved popularity of books such as

James Gleick's {\it Chaos} and Stephen Hawking's {\it A Brief History of Time}. Apparently, people are interested in science and want to understand how it effects their lives. In this atmosphere there is a tendency to hype science. Much of the current debate over the sciences of complexity examines whether ideas such as `the edge of chaos,' and `self-organized criticality' have been oversold. If they have been, we soon will know. Even if those particular ideas turn out to be bogus, these four books will still be read: after all, no bestiary would be complete without a unicorn.

In fact, while the debate continues, the sciences of complexity have quietly pervaded everyday science and engineering. Almost a decade ago, having just received my Ph.D., I attended the first Santa Fe Institute summer school for the study of complex systems. There I learned about many of the techniques described in these books, such as genetic algorithms, cellular automata, and simulated annealing. At the time, those techniques seemed to me far out, abstract, and not necessarily practical. Now I am a professor in the department of Mechanical Engineering at MIT. While I write this, graduate students are applying genetic algorithms to find the least wasteful way to stamp parts out of sheet metal, programming cellular automata to analyze air conditioning, and using simulated annealing to optimize designs for engines. Ideas from the theory of information and computation are woven together in a method called Axiomatic Design, and put to work making better freezers and injection molds. A good working definition of a complex system is one that has to get and process large amounts of information in order to function. Cells, brains and ecosystems are not alone in their complexity: increasingly, they are being joined by buildings, cars, and washing machines. The systematic study of complex systems is here to stay.

Not that there was ever any doubt about its staying power. All of the goals, and most of the basic ideas of the sciences of complexity have been around for as long as science itself. Anyone who regards artificial life composed of self-reproducing automata as a futuristic idea should read the second sentence of Hobbes's {\it Leviathin} (1651): `For seeing life is but a motion of limbs, the beginning whereof is some principal part within; why may we not say, that all {\it automata} (engines that move themselves by springs and wheels as doth a watch) have an artificial life?' Indeed, why not?

One of the first and best books on the sciences of complexity is {\it The Dreams of Reason,} by Heinz Pagels. Published in 1988, not long before Pagels' tragic death in a climbing accident, {\it The Dreams of Reason} explores the role of reason in the irrational human need to understand. Noting that this irrational urge has historically co-opted all available rational tools, Pagels argues that the future of science lies in the synthesis provided by information and computation. Tall, flamboyant, and fond of a good intellectual dust-up, Pagels was the real-life model for the chaotician Malcolm in {\it Jurassic Park}. Unlike Malcolm, he can't be resurrected for a sequel, but if he could read these books and their reports on what the study of complex systems has accomplished recently, he'd probably smile, and he'd certainly say, `I told you so.'

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Complexity is often confused with chaos. Murray Gell-Mann, author of {\it The Quark and the Jaguar}, a book that contains an engaging and penetrating discussion of the sciences of complexity, claims never to have given a talk on complex systems without someone coming up afterward to thank him for his talk on chaos theory. In fact, chaos is only one of the sciences of complexity. For all its ominous name and the hoopla surrounding its popularization, chaos is a relatively narrow mathematical discipline that concentrates on classical, deterministic, dynamical systems; and the scientific successes of chaos theory come from the intensity of its narrow focus.

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Bits and Bucks: Modeling Complex Systems by Information Flow

Seth Lloyd, MIT; Thomas Lloyd, McKinsey

Extended Abstract:

This paper presents a general method for modeling and characterizing complex systems in terms of flows of information together with flows of conserved or quasi-conserved quantities such as energy or money. Using mathematical techniques borrowed from statistical mechanics and from physics of computation, a framework is constructed that allows general systems to be modeled in terms of how information, energy, money, etc. flow between subsystems. Physical, chemical, biological, engineering, and commercial systems can all be analyzed within this framework.

Take, for example, trading over the internet. Each flow of information (measured in bits per second) is associated with a flow of energy (measured in watts). The energy per bit -- effectively, a form of temperature -- is a crucial quantity in characterizing the communications performance of the network in the presence of noise and loss. But each bit can also be associated with a monetary value (bucks), as when the title to some commodity is transferred electronically to a buyer and an electronic draft to pay for the commodity is transferred to the seller. The bucks per bit -- again, a form of temperature -- is a crucial quantity in deciding whether to buy or sell. Clearly, some bits are worth more than others!

This paper shows that in complex systems that can be accurately described by such a modeling framework, different structures for interconnects and protocols for exchange can lead to qualitative and quantitative differences in behavior. In some cases, such as thermodynamic systems, stable behavioral equilibria exist and exhibit gaussian fluctuations. In other cases, such as phase transitions and systems of economic exchange, quasi-stable or unstable equilibria exist and exhibit power-law fluctuations. Finally, some types of flows yield no equilibrium at all. The framework makes quantitative predictions for the efficacy, flexibility, stability, and robustness of complex systems characterized by flows of information together with energy, money, etc.

To quantify and relate flows of information and energy/money, model the system to be analyzed as a directed graph. Each vertex of the graph corresponds to a subsystem at a particular point in time, so that the graph represents a `space-time' picture of the complex system. Each directed edge represents a path along which information and energy/money can flow. To preserve our ordinary notions of causality, flows are directed from past to future. The graphs are acyclic (no time travel). The requirement that different quantities such as energy and money are conserved leads to constraints on the flows: the total amount of a quantity flowing into a vertex is equal to the total amount flowing out.

Flows are inherently dynamical. To specify the dynamics of the model in the most general way possible that respects the causal structure, consider a Markovian dynamics in which the probabilities that a system is in a particular state at a particular time are functions of the states of its inputs. A directed graph associated with a Markovian

dynamics of this sort is called a Bayesian network. The probabilistic dynamics together with the conservation laws causes the conserved quantities to diffuse throughout the network according to a well-specified dynamics, a potentially complex diffusion equation.

The Markovian dynamics allows one to assign a joint probability distribution to the states of all the vertices and edges. Consequently, each vertex and edge also has a well defined quantity of information associated with it. Similarly, mutual and conditional informations are well-defined. That is, the Markovian dynamics allows one to quantify the amounts of information flowing through the graph.

This framework is potentially very powerful: it can represent the probabilistic dynamics of essentially any physical system (discretized in space and time). For example, the action of a digital computer can readily be mapped onto this framework, where the vertices represent logic gates, the edges represent wires, and the graph as a whole represents the wiring diagram for the computation. So this framework can clearly represent any process that can be simulated on a digital computer. Indeed, if the nodes represent quantum logic gates, and conditional probabilities are replaced by conditional probability amplitudes, the framework can be used to represent any computable quantum system, including a quantum computer. Since quantum computers can simulate all known quantum systems to an arbitrary degree of accuracy, this framework is capable of representing an arbitrary physical dynamics.

This paper will focus on the application of the bits/bucks framework to engineered and financial systems. The usefulness of the framework for any given system will depend on the ease with which the system's operation can be mapped onto the framework, and on the complexity of computing the dynamics of the resulting model. We will investigate the application of the framework to physical systems such as fluid flows, to complex engineered systems such as automobiles, and to financial systems such as a commodities exchange.

An Attempt at Complex System Classification

C. L. Magee and O. L. de Weck

Summary
The remainder of this paper is organized as we currently intend to organize the final paper. However, the content is not a shortened version of the final paper but instead a status report on the development of the content.

Introduction

There are three inter-related reasons for attempting a system classification study at this time. By analogy with other fields, a classification framework has often been a major step forward and a significant accelerator of development of the field. Thus our first reason for undertaking this work is as a possible small "foundation" contribution in the field. For definitions, we rely on previous work by the ESD committee.

A second related purpose is that by developing a framework for classification of complex systems, we may help delineate the "intellectual boundaries" of engineering systems. Such delineation may be of interest within MIT in differentiating ESD from engineering departments, the Sloan School and other areas as well as outside MIT in the broader academic setting. We presume that such boundaries will be open and blurred as are those defining other fields.

The third and to us most important reason for attempting to classify complex systems at this time is to make a contribution to the engineering/design of such systems. As the modern world relentlessly evolves towards a highly interactive and interdependent complex set of complex systems, the improvement of our ability to conceive, design, implement and operate such systems is becoming among mankind's highest needs. Perhaps the major design question revolves around the issue of designing for future design and use flexibility (reuse architecture).

Approach

Our approach has been to assess the utility of prior classification frameworks and then to extend them and develop new ones by both top-down and bottom-up techniques. In order to assess the utility of a framework, we are focusing on a "testbed" list of complex engineering systems. We are updating the list based on feedback from other ESD faculty but results at this point relate to the original list only. We intend to go through another round of dialogue with the ESD faculty before finalizing the list.

In addition to the list we have developed a set of criteria for determining whether a given classification framework is useful. The first criterion is that it must work for the systems we are trying to engineer more effectively (hence the list as "testbed"). To have utility, a framework must first and foremost be able to differentiate among systems on our list based on some system attributes and separate them into distinct groupings. In addition, valuable classification schemes would help by defining categories where different engineering methods and approaches are most useful. A useful framework would also possibly help define potential issues and solutions in various categories suggested by the framework. Finally, a useful scheme might suggest the most viable modeling and representation techniques to apply in different categories.

Using these criteria and the preliminary "testbed", we first assess prior classification frameworks for complex systems (next section). In the final two sections we briefly discuss our status on our top-down and bottom-up approaches to developing new classification frameworks.

Existing Classification of Complex Systems

Three existing classification frameworks have been examined and tested with our preliminary list of complex systems of interest. The first of these is due to Bartalanffy who extended Boulding's work. These frameworks were suggested as part of their efforts on "General System Theories" in the 1950's. The list as presented by Bartalanffy had a strong orientation towards his discipline of biology and is summarized in Table 1.

Table 1 Systems classification according to Bartalanffy

Static Structures
Clock Works
Control Mechanisms
Open Systems
Lower Organisms
Animals
Man
Socio-cultural Systems
Symbolic Systems

In this list each successive item is meant to be more complex and to some degree to incorporate the preceding entries. In addition, Bartanlaffy suggests the "theories and models" useful in each level of the hierarchy. Although this is the kind of utility we would like, this framework fails our first criterion as it does not apparently differentiate among our systems of interest. All of the "testbed systems" are similar combinations of the last three levels in this hierarchy.

A second approach from within the European Systems Engineering tradition is due to V. Hubka in his book-"The Theory of Technical Systems". His framework also separates technical and human systems and further delineates the technical systems according to academic disciplines. Again this framework fails our first criterion as it does not differentiate among our systems of interest-all are at his highest category.

A third classification framework is also from the European Systems interest and is of recent development by Buechel et. al. This is based on system attributes as shown in Table 2 below.

Table 2: System Classification according to A. Buechel et al. (modified)

<table>
<tr><th>System Attributes</th><th colspan="6">Attribute Value</th></tr>
<tr><td>realm of existence</td><td colspan="3">real</td><td colspan="3">virtual</td></tr>
<tr><td>origin</td><td colspan="3">natural</td><td colspan="3">artificial</td></tr>
<tr><td>boundary</td><td colspan="3">open</td><td colspan="3">closed</td></tr>
<tr><td>time dependence</td><td colspan="3">static = time invariant</td><td colspan="3">dynamic = time varying</td></tr>
<tr><td>system states</td><td colspan="2">continuous</td><td colspan="2">discrete</td><td colspan="2">hybrid</td></tr>
<tr><td>predictability of system behavior</td><td>deterministic</td><td colspan="2">stochastic</td><td colspan="2">indeterminate</td><td>chaotic</td></tr>
<tr><td>degree of system complexity</td><td>simple</td><td colspan="2">moderately complex</td><td colspan="2">highly complex</td><td>extremely complex</td></tr>
<tr><td>system control</td><td colspan="2">open loop</td><td colspan="2">feedforward</td><td colspan="2">feedback control</td></tr>
<tr><td>human involvement</td><td colspan="2">human operated</td><td colspan="2">semi-autonomous</td><td colspan="2">fully autonomous</td></tr>
<tr><td>System size</td><td colspan="2">small</td><td colspan="2">medium</td><td colspan="2">large</td></tr>
</table>

Our systems of interest are all real, artificial (with possible natural sub-systems or natural systems interacting outside the system boundary), open, dynamic, large, highly to extremely complex (by some definitions) and have human involvement. Nonetheless, it may be possible to use the predictability and system control attributes to obtain some differentiation among the systems in our list. The system classification aspects related to their control and flow of information within the systems suggests a link to the cybernetics literature. Thus, we are still pursuing this framework but at present expect only limited utility of this approach with our systems .We are also examining other ideas such as "system archetypes" from the Systems Dynamics Literature as to their value in a classification framework.

New Classification Frameworks

In order to develop new classification approaches that may be more useful, we are simultaneously pursuing top-down and bottom-up quantitative perspectives. It has been a major premise of our work that the classification framework will have to involve more quantification in order to be highly useful. The need to do this is empirically apparent when one attempts to differentiate among our systems of interest with prior classification frameworks (see preceding section).

Bottom-up Approach

This is basically an "experimental" approach, which examines various quantitative attributes of existing systems (the "testbed"). The hypothesis is that comparison of the appropriate quantitative attributes across a range of systems will define or lead to new classification frameworks. Ashby has made multiple plots of application properties of existing materials of all kinds and many of these "naturally" separate well-known categories of materials such as ceramics, polymers, metals etc. into different sections of the complex plots. A hypothesis we are testing is that similar plots of the appropriate attributes of engineering systems of interest will lead to clusters of significantly different engineering systems. A second working hypothesis is that the attributes we use to characterize the systems are the key to determining the value of any classification framework we propose.

Our experimental approach to finding the appropriate attributes is to iterate among attributes depending on the utility found with the preceding trial. Thus, using the testbed we are attempting to devise and use a robust set of attributes to maximize the utility of the resulting classification framework. The attributes to be studied include:

SYSTEM STATIC QUANTITATIVE ATTRIBUTES: mass, energy, information, cost/dollars to develop and build, people (manhours to build, R&D hours to develop, manual vs. knowledge content), volume occupied, interface length or area.

DYNAMIC QUANTITATIVE ATTRIBUTES: mass flow, energy flow, information flow, value added (dollars) per day, manhours worked (manual, intellectual etc.).

VARIATION: Quantification of stochastic variability of the static and dynamic variables is difficult but probably very important for achieving a useful classification framework. E.g. assess rate of change or substitution of system elements.

SYSTEM STRUCTURE: This is another important but difficult to measure aspect of complex systems. It is difficult to measure because quantification of this attribute is unknown to the authors but notions of DSM density may be developed to quantify internal or external interactions which are a key element in structure.

SYSTEM FUNCTIONS: The basic functional purposes of our systems are being examined to see if these help achieve a useful classification framework.

SYSTEM ATTRIBUTES RATIOS: These may prove the best way to achieve classification results of high utility. Example ratios include $/lb., R&D$/joule, manhours/lb., manual manhours/information manhours, interface area/volume, etc.

Top-down approach

This work essentially involves review of the literature for complex systems theories. The purpose of our review is to find classification schemes or parameters of importance that may become attributes for our experimental or bottom-up approach (if successful this might represent a “middle-out” approach).

The theoretical frameworks of importance in the General Systems era included cybernetics and information theory and some aspects of these may contribute in our current efforts. The more recent attention to complex system theories has been considerable. This “modern” complexity theory is described by some as having roots in economics, evolutionary biology and statistical physics. Some of these models have been compared to quantitative aspects of complex systems but these are still rare and to our current knowledge not for the kinds of systems on our list. We plan to use these theories to the extent possible to guide us in attribute selection for our bottom-up studies.

Concluding Remark

The major challenge over the next few months will be obtaining sufficient quantitative data about systems of interest to make meaningful progress in the experimental approach at the heart of our paper. We believe by being flexible about the possible parameters/attributes being studied we maximize our chances of having enough data to test the ideas and perhaps develop something of real interest. We are trying to enlist UROP students (and any others) in helping gather, plot and interpret data.

The Evolving Role of Systems Methodology For Seeking Pathways to the Future In Large Scale Open Systems

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Based on thirty-plus years experience in exploring future scenarios for large-scale energy, environmental and resource systems, this paper offers an appraisal of where such activities are and where they are going. There are two ways of addressing this. Process: How are such exercises carried out, and Methods: Are new methodological advances emerging and how will they change the business of looking for pathways to the future. New advances in information technologies and computation, deeper thought about the metrics for measuring system performance (the "ilities"), and better systems methods in simulation and dealing with uncertainty and consumer psychology will make this process more productive and more insightful. How soon will we be able to combine analyses of technologic alternatives along with a better understanding of institutional structures, regulations, business strategic planning and economic incentives in detailed simulations? From a process point of view, an evolving philosophy of "no optimal path", stakeholder involvement, transparency of assumptions, data mining and wide ranging analysis of many different scenarios form a more enlightened framework for employing these new tools.

Consider two motivating examples for pathways to the future for energy choices in the 21st century. One is a long-term Fossil Fuel-based scenario - in which our concerns about global warming and the environmental impacts of use are not strong enough to change quickly from a fossil fuel pathway. In this scenario, fossil fuels perhaps aided by Nuclear Energy, will be kept vibrant by advances in production, transmission, and use, which will allow us to be more energy efficient and reduce environmental impacts. In the second scenario, Decentralized Energy – in which global warming issues do become important – we will see a movement towards an electricity-based and/or hydrogen-based largely decentralized energy carrier system. Here energy production would depend more on renewables or hydrogen manufactured in distributed place, rather than in large complex central facilities, and a replacement of mobility of people by information technologies in a great many cases. More intelligent use would be the hallmarks of both approaches.

In the aftermath of September 11, as security of fossil fuel availability becomes more questionable; we see a merging of these two streams of thought towards a much more decentralized production of energy for stationary and mobile needs even before fossil fuel sources are stressed. To quote "Just as the stone age did not end for lack of stones, the oil age will not end for lack of oil".

At the heart of the analysis of this transition are complex system models, which can help to evaluate strategies for the operation and location of small almost selfgenerating power, mobility systems, employment, education, and health care delivery. These are, at their core, socially-driven technical systems with strong inputs from public decision-making, as well as private strategy. The interplay between public policy designs and the instruments to implement them, and proactive and reactive private response, will be better understood by systems-based methodological advances and their implementation in new methodological frameworks.

Research on Frameworks - the Process Issues

1. The past is prologue to the future: As we look to future problems, it is necessary to characterize the current state of affairs and the trends and actions that put us here. This is a non-trivial exercise, which involves extensive data collection. It is the place
   Where stakeholder alliances are forged and rules of engagement set for a successful process.
2. The metrics for evaluation of the present and the future must be thought out carefully- Some recent experiences with such "ilities " as sustainability are discussed. An important issue is how uncertainty is dealt with.
3. What are the Pathways to the Future? In the words of Greg McRae "at least get the sign right". As engineers in large-scale open-systems become more conversant with economics and social sciences, the subtle issues of quantification vs. non-quantification will be addressed and simulation across a wide breath of supply alternatives and demand responses will become far more commonplace.
4. The framework for evaluation of results, stakeholders' display of assumptions and information will become a main stock in trade for engineering systems practitioners.

Research on methods

1. Life Cycle Tools

A closer attention to extended life cycle analysis to understand and weigh impacts on economic, social and environmental goals of products and processes. Exciting new work using the internet to limit time-consuming data gathering will lead to faster and better prototyping and the search for more innovative uses of materials and energy.

2. Complex Simulation Under Uncertainty

A new generation of stochastic tools capable of exploring risk vs. efficiency tradeoffs in large-scale quasi-public systems (water, energy, etc.) is now evolving. A rebirth of interest in Systems Dynamics and other simulation tools combined with economic and decision analysis tools, are forming a whole new way of looking at options. In these large quasi-public systems, issues such as redundancy and resilient protection from extreme events vs. "efficient systems" and their impacts on economic and social goals will need to be studied.

3. Decentralized Systems Management Tools

Strategies for the decentralized operational management of complex systems from traffic - to home energy use - will be developed depending heavily on information technologies.

4. Focus on the Behavioral

Understanding of end-use demands and consumer preference and the impacts economic and other regulatory instruments on them will become a more central theme. This requires a movement from the more traditional concept of building to meet externally- specified demands (a supply philosophy) - to a greater consideration of how demand modifications in types, locations, and timing of use can be integrated into decision-making (supply demand interaction). Much closer alliances with the social science outside of economics and political science will be needed.

5. Tools for Stakeholder Involvement

As these systems have stakeholders outside of industry and government, tools for educating and building consensus about difficult tradeoffs will evolve much more quickly. Here visualization and tools for exploring complex tradeoffs between important economic environmental and social goals will be a central theme.

In an increasingly urbanized and increasingly populated world, how will societies deal with basic concerns for security, education, clean water and air, mobility, employment, and other components of an adequate quality of life? The 33 percent increase in world population projected in the next 30 years will occur largely in rapidly urbanizing developing world countries. Only by viewing the sustainability of future settlements as complex systems can these basic tools need be met. Key elements will be new institutions, and a greater emphasis on technical systems powered by information technologies. Systems methods will be at the heart of tools needed for decision-making about future trajectories.

Three Regimes of Systems: Historical Perspectives on Systems Thinking in Engineering

David A. Mindell

This paper surveys the history of systems thinking in engineering in the United States, from the late nineteenth century to the present day. The history can be divided into three phases. In each phase, engineers concentrated on certain kinds of technical systems, and developed types of systems thinking to deal with them. First, from the late nineteenth century to World War II, systems thinking concentrated in the electric power and telephone industries and focused on interconnecting disparate elements into larger wholes, frequently for systems spread over large geographic areas. Second, the imperatives of World War II led engineers to conceptualize systems as integrated, dynamic entities, and to formalize methodologies for managing the complex organizations to design and operate such systems. This phase flourished in the Cold War, although its techniques are still with us today in selected areas. The third phase, what we call Engineering Systems, began to emerge in the 1990s when engineers began to expand the boundaries of technical systems to include not only their internal or organizational dynamics, but also broader social and industrial contexts. They also recognize that the complexity of these systems means that accurate prediction or even simulation is not always possible.

At the turn of the 20th Century, two new systems dominated the technological landscape: electric power and the telephone network. Thomas Edison designed not only light bulbs, but a system that also included generators and transmission lines to compete with gas lighting. By the 1920s, engineers conceptualized electric power systems as sets of interconnected elements like generators, motors, traction loads, or transmission lines each of which could be designed and analyzed independently. In the 1920s, as local or regional power networks connected into national "grids" or "superpower" systems, the new entities began to exhibit new behaviors that could only be understood by looking at the system as a whole. Still, within this engineering culture engineers tended not to use self-conscious language of "systems" to describe their work, although managers did increasingly see the system as including both physical power networks and the organizations that supported them.

In the telephone network, by contrast, the language of systems was more explicit. AT&T chief Theodore Vail's famous motto "One policy, one system, universal service," captured the company's totalizing view, though its network was composed of vast numbers of small, interconnected units. Within AT&T, engineers referred to their national network as "the System," and beginning in the 1920s the company had job titles for "System Engineers" and "Systems Development" departments. Yet these engineers did not have the most abstract view of the system, but rather concentrated on its concrete manifestations: the equipment layouts, power systems, and wiring diagrams for local substations. When Bell Telephone Laboratories was founded in 1925, engineers did begin to study the abstractions of the system like the statistics of switching, and the interchangeability of bandwidth, but systems were still understood as hierarchical assemblies of component parts, with unidirectional, linear interactions.

The second phase of systems thinking began to emerge During World War II. In response to technical problems like radar and automatic gunfire control, engineers now conceptualized their systems as dynamic, integrated entities with feedbacks, where the behavior of each part helped determine the behavior of the whole. New techniques arose from the merger of servomechanism theory, communications theory, and feedback control. The term "system engineering" emerged to capture the sense that the products of advanced engineering, particularly in the military realm, could no longer be considered as individual machines or things but as systems: an aircraft was no longer simply a machine, but a collection of systems, for engines, fuel flow, structure, controls, etc.

Technical and organizational currents in the second phase of systems coalesced during the Cold War. For the Atlas project to build the first ICBM, the prime contractor was no longer an airframe manufacturer but rather a system engineering corporation, in this case Thompson-Ramo Woolridge (TRW). A similar set of systems oriented companies appeared, frequently in new organizational forms like RAND and MITRE. During the 1950s, a host of new disciplines appeared that we might call the systems sciences, including cybernetics, operations research, general systems theory, systems analysis, and systems dynamics – each had its own techniques, its own home institutions and its dominant professions. All viewed the world in terms of flows, feedbacks, and interactions, and analyzed systems by breaking them down into component parts, understanding the characteristics of those parts, and then recombining them. These approaches were considered "engineering science," wherein expert analysis brought objective, quantitative analysis to complex problems, from nuclear targeting to the economics of innovation. They were characterized by the belief that experts, computers, and numbers could overcome politics and personal influence, which were considered irrational.

The Cold War systems sciences achieved great success, particularly in areas with clearly defined technical goals, like the Apollo project -- explicitly modeled on the Atlas program and hailed as a triumph of systems engineering. The systems sciences also overreached, however, and met their limits in Vietnam, the Great Society programs, and other civil systems with complex interactions, heavy political components, and and vaguely defined boundaries.

In the last decades of the twentieth century, the third phase of systems thinking, which now goes under the rubric "engineering systems," subtly began to emerge. Engineers recognized that technological systems exhibit complex behaviors that are rational, but not entirely predicable. As Thomas Hughes argues, late-century engineering projects like the Central Artery and Tunnel in Boston began to treat the "messy complexity" of politics, social movements, and local interests not as external influences to be factored out, but as internal variables. The internet made it clear that distributed, unplanned systems could grow to be incredibly complex and powerful. Engineers increasingly turned their attention to large (sometimes global-scale) systems that exhibit complex behavior. At the same time, computer and simulation technologies advanced to the point where systems as complex as the global climate could be modeled with some degree of confidence, and used as a basis for making policy. Joe Sussman describes this era with the term CLIOS (Complex, Large, Interconnected, Open Systems) that explicitly include social, political, and economic variables in their models and definitions, and other new formulations are emerging as well.

These three phases do not constitute a linear progression; rather today's systems landscape has elements from each phase, and each generation incorporates and furthers the ideas of the former. Still, the historical schema of three phases clarifies the issues at stake in defining Engineering Systems today and places it in historical perspective.

Large Scale Infrastructure Systems

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Large-scale infrastructure systems are at the nexus of three systems; social systems; natural systems and technological systems. The social system generates demand for services of the systems, establishes the regulatory framework for their realization, operation and abandonment, and provides the economic systems whereby necessary resources (capital and labor) can be mobilized for their operation.

The natural systems, used to be considered a barrier that challenged our ingenuity to overcome. However, in the past few decades it has become a concern on how to protect it. Large infrastructure systems have impacts on both the ability of the natural system to supply the resources needed to build and operate them, as well as the ability of the nature to absorb the waste that infrastructures generate. This concern over "the source and the sink" ability of the nature has imposed new constraints on infrastructure with a very far reaching implications to planning design, construction, and operation and management of all kinds of infrastructure.

The technological systems are basically the enabling means to create facilities that will meet the society's need without straining our natural systems. Several examples from hardware and software sides of technology will be used to demonstrate their enabling capacity.

There are generally two types of large scale infrastructure systems: first type consists of very large, complex and, costly systems that require all components to be in place before the system can be operational. Examples are power plants, petrochemical plants, skyscrapers, and environmental remediation facilities. The second type of large scale infrastructure systems is composed of many parts, each by itself a functioning element and each requiring a small to medium size budget. As long as the parts are geographically dispersed, they function independently with rather well understood and predictable behavior. However, when these parts become more densely clustered geographically or interconnected operationally, they form a larger system with complex performance and they begin to affect and interact with non-built systems. In this category, the infrastructure draws its complexity primarily from its network characteristics. Examples, include; transport systems (highways, railroads and waterways), sewage systems, power distribution networks, and communication networks. Large-scale systems with similar characteristics can also be defined with respect to housing. For example, each housing unit is a relatively small project, but collections of them create neighborhood communities and suburbs that have significant environmental, social, and political consequences, that are not dominant in a single unit.

Prior to World War II, most projects of the first type (commonly referred to as "megaprojects" or "macroprojects") were basically conceived by visionary individuals, who championed their cause; Suez Canal, Panama Canal, Brooklyn Bridge are typical examples. The technical feasibility and cost effectiveness of these projects were often dubious, and were mostly wrapped in national flags and national pride. Fortunately a very small number of these visionary schemes were ever realized. When they were undertaken, however, they had, without exception, substantial cost overrun, longer time to finish, and significant unanticipated political, social, economic and environmental consequences.

It is only very recent, since World War II, that the scope and scale of some industrial projects have placed them in the megaproject league, and have forced corporations such as petrochemicals, utilities, oil and gas, and automobile to seek a more holistic approach to their undertaking. For example, if one looks at new auto manufacturing plants and considers the extent of involvement and interest of local communities, states and even nations (e.g., Mexico and Brazil) in locating such plants in their territories, one can begin to gauge the complexity and magnitude of the consequences of such undertakings. Likewise, when viewed from the perspective of the auto industry and the intangible factors that enter into the appraisal and planning of new manufacturing facilities, it is apparent that the engineering and construction aspects of the project seldom are a decisive factor, even thought they may involve expenditures of several billion dollars.

The construction phase of megaprojects requires the concentration of large amounts of resources (manpower, equipment and materials) in a very limited physical area over a finite number of years. The primary skill required is as much managerial as it is technological. Thus the success or failure of these projects is highly dependent on the quality of the management team. The management skills required, in addition to having a program for the control of resource utilization, include the ability to build consensus among the three key parties involved; i.e.; financier (owner), engineer (designer), and contractor (builder). Each of these parties has a different set of objectives and interests in the project. For example, the financier is concerned with return on investment and thus gives emphasis to cost and schedule controls. However, the contractor wants profit maximization and therefore may seek change orders, which increase costs and on many occasions actually prolong completion time. Many complex and innovative contractual arrangements and management skills have been developed to avoid the inherent conflicts among the interests of the three parties. These arrangements and skills are highly grounded in the scoio-cultural traditions of the parties, are contextual in nature, and not easy to transfer. The core issue of concern in these megaprojects is to better understand the dynamics of the relationships among the three parties. The users of the output of these megaprojects in industrial sectors are separated from the facilities and the units are operated by professionals.

The second type of large-scale system (e.g., those consisting of a network of large number of simple elements) is interesting from the standpoint of system performance. While the construction phase of such systems is not complicated, any additions to or deletions from the system often create socio-economic concerns that significantly complicate the development of the public consensus needed for their construction, operation, and management. The NIMBY (Not In My Backyard) syndrome is a typical manifestation of public concern over any change to the status quo of these systems.

In this type of system, owners, contractors and users usually have conflicting objectives, which require a consensus-building approach rather than an analytical approach to change. Since these systems are by nature very pervasive, their significant interaction with social and natural environments create complexities that go well beyond their physical development. Transport systems in particular have been the prime example of this situation. Over the past few decades, it has not been possible to add new transport facilities to the existing system in the U.S. A few that have been built have not been scrutinized on a conventional economic-evaluation basis, their engineering feasibility has been taken for granted, and most have been built using the broader context of social desirability (the least common denominator). For example, on several occasions transport facilities have been abandoned or intentionally underdesigned due to social, political, or environmental concerns. A lack of understanding of these dimensions on the part of the engineering profession has been a primary cause of cost escalation, delay, reduction in scale and scope, and at times complete abandonment of projects. Many in the engineering profession hold on to the belief that public hostility toward such projects is due to public ignorance rather than due to inadequacy of our engineering approach.

This paper elaborates on the evolution of infrastructure systems design, construction and operation. It attempts to demonstrate the sources of complexity and discuss the manner by which they come about and interact with our social, natural, and technological systems.

The Anatomy of Large Scale Systems

Joel Moses

EXTENDED ABSTRACT

Most theoretical analyses of systems emphasize their behavior. In this paper we shall emphasize the role of organizational structure in influencing certain aspects of the behavior of systems, rather than the full behavior of the systems. There are several historical examples where structure was analyzed early on in order to gain a better understanding of systems. In medicine, for example, anatomy was studied well before we had a deep understanding of the role and behavior of subsystems or infrastructures of the body, such as blood flow. Different anatomical structures provide different advantages and disadvantages in coping with changes in the overall environment in which a living system is expected to operate.

We shall emphasize three major organizational structures for large scale systems. The network structure permits one to create a very large system, albeit one which may not be easy to control. The tree structure is a hierarchical form that is very common, both in human organizations and in engineered physical or abstract systems. The layered structure is also a hierarchical form, but is not as well understood. Layered structures occur in large partnerships and in physical systems that have a clear separation between the layers. We claim that large scale systems employ mixtures of these forms. We indicate advantages and disadvantages of these three generic organizational forms. We also relate the forms to certain system properties, in particular flexibility. Finally, we relate organizational structures and system properties to the notion of structural complexity.

Every system will have some amount of complexity, and large scale versions of systems will tend to have more complexity than smaller versions. What frustrates people is when a system is so overly complex that it is difficult to make additional changes in it. In fact, many Americans seem to believe that this is a property of all large scale systems. How does an overly complex system arise? Initially tree structured systems will appear relatively simple. As requests for changes are made, there are two basic strategies for implementing them. One is to restructure the system from scratch for each request, thereby keeping the revised system relatively simple. Since this approach is quite time consuming and expensive for large scale systems, the alternative approach is usually chosen. This approach reuses most of the components or modules of the original system, and modifies some of the interconnections among them. Such modifications will usually lead to non-standard structures and greatly increase the structural complexity of the resulting system. The reason that nearly all new connections in a tree structure are non-standard is that the only legal connections are to one's parent node and to one's children nodes, and unless the new connection is to a new child node it will be non-standard.

Layered structures have an architecture that permits certain types of changes to be made easily. This is because nodes at one layer can be legally connected to any node at the

layer immediately above, immediately below or the same layer as them. Thus changes in specifications that require nodes to be connected to other nodes can usually be readily made, and with relatively little growth in structural complexity.

Large scale infrastructures, such as ones for electric power and telecommunication, can be viewed as having three layers. The bottom layer in the electric power system has the generating plants, such as nuclear power plants. The middle layer has the transmission and distribution systems, and the top layer has the end users, such as refrigerators. Of greatest interest to us is the middle layer that may contain both networks and hierarchies.

Human organizations may benefit from mixtures of organizational structures. For example, a tree structured project organization may overlay a layered structure used for mentoring. If middle managers play a dual role as project managers and as mentors in such an overlayed structure, we have an alternative to a matrix system, and one that we believe is used in some large Japanese organizations.

What gives layered systems and networks their particular advantage in situations involving high rates of change is their flexibility. We measure flexibility in a hierarchical system by the number of paths from the top node to the end nodes, counting loops just once. Tree structures have a unique path to each end node, and are thus relatively inflexible. Layered systems have a geometrically growing number of paths, depending on the number of layers. Adding connections to a tree structured system adds relatively little to its flexibility at a non-trivial increase in structural complexity, due to the non-standard nature of most new connections.

Tree structured systems are often products of a reductionistic approach to design. Layered systems tend, on the other hand, to be relatively holistic, since nodes at the same layer are at the same level of abstraction. Product platforms are closely related to layers, and usually arise from the creation of standards. Neither of these architectures is ideal when the rate of change is very high. In such cases, small team-based architectures may be most appropriate.

Historically, different system philosophers have tended to emphasize one or the other of these two hierarchical architectures. For example, Plato thought in terms of layered systems, and Aristotle, his student, emphasized tree structures. Various cultures emphasized one of these two forms at different times in the past. Cultures based on multiple religions, such as the Japanese or German cultures, can simultaneously have the advantages (and disadvantages) of both of these architectures.

References

1. Jay R. Galbraith, *Competing with Flexible Lateral Organizations,* 2nd edition, Addison Wesley, 1994
2. Herbert A. Simon, *Sciences of the Artificial,* 3rd Ed., MIT Press, 1996
3. Herbert A. Simon, "Complex Systems," in Computational and Mathematical Organization Theory, Kluwer, 2001, pp.79-85

Lessons from the Lean Aerospace Initiative

Prof. Earll Murman and Prof. Thomas Allen, Co-Directors Lean Aerospace Initiative

Top Level Issues

The intellectual foundations of Engineering Systems will develop in large part, from empirical research and eventual codification. While large-scale systems have been studied in the past, usually this has been of single, unique projects or programs. What is required now is a more systematic and programmatic approach. Although it is difficult to find multiple examples for comparative analysis, the effort to do so must be made. It is only through multiple observations that there can be any hope for generalizing results and for gaining genuine theoretical insights. Simple project reports or case studies can often provide leads for further investigation, but that investigation must be done on a systematic and rigorous basis, if we are truly to learn anything.

Such an ambitious goal is not going to be accomplished easily. It will require field observation of the development and implementation of multiple systems. Aside from the difficulty of finding appropriate examples, this implies satisfying the needs of many stakeholders. Experience tells us that gaining access to live field data requires not only minimizing interference but frequently requires a quid pro quo. We have to combine some short term payoff for stakeholders as well as a long term increase in understanding. This short term goal is often easy to fulfill in the form of providing a "benchmark" data or advice to the stakeholders. It must be included in the research plan, however, and offered at the time of negotiation for access. Many times there may be a variety of stakeholders, not all of whom will be satisfied with any particular payoff (e.g. management and organized labor). This aspect must also be taken into account in initial planning and incorporated into the business plan.

Real World Research

(There are a number of textbooks covering these issues, so we will only highlight here.) Field research differs from laboratory research primarily in the difficulty of measuring and controlling variables. For the results to be valuable to either theorists or managers there must be some outcome or dependent variable to which observations can be related. In the case of managers, this outcome is usually preferred in the form of some indicator of individual, group or organizational performance. The chief difficulty that this presents is that there are usually a very large number of contributors to such an outcome measure (Take, for example, the determinants of corporate performance.) This then requires either the gathering of a very large data sample (in the hope that uncontrolled variables will be randomized) or the controlling of all but the variables that are directly under study or manipulation. Both of these solutions are very difficult and usually impossible to implement. As a compromise, we are thus driven to measurement at a lower level of analysis (e.g. organizational sub-unit, group or individual). The choice of level or unit of analysis is critical and frequently a study can be done at several levels, provided that clear distinctions are made in both the analysis and presentation of the data.

Despite all of these difficulties, good field research on engineering systems can be accomplished even to the extent of field experiment. Changes can be introduced, for example, into the way in which a system development is managed. This can enable the measurement of "before and after" effects. Frequently this can be done with inclusion of a control group receiving all but the experimental change (Cf Allen and Gerstberger, 19--). At other times studies can be "trimmed" as is often done in agricultural research and in the study of human development. Two activities many be underway in different organizations or in different parts of the same organization. If different approaches are taken, this provides a natural experiment with many variables directly controlled (Cf., Allen, 1984).

Field research often requires observation over an extended period of time. This can be both and aid and a difficulty. When events that occur over the time period can be observed or measured their effects can often be ascertained. When they occur unobserved and unmeasured, they may introduce noise leading to false conclusions.

Learning Community
The ideal way to organize a program of research in engineering Systems is to first identify all of the stakeholders. There may be a single government agency or firm or there may be several, organized in a consortium. Following this, one must identify all of the value streams. Where these conflict (and they often will) there needs to be identification of potential conflict and terms of engagement should be specified for managing such conflicts. For example, there is often a conflict between the academic need for open dissemination of knowledge and the industry need to protect knowledge for competitive advantage. There may sometimes be a need to discontinue a program and move to new challenges that conflict with a perceived need to maintain employment for those working on the program. Such conflicts can be managed, but they must be faced early and terms worked out.

Once all stakeholder value streams have been identified, a management structure can be specified that recognizes the multiple value streams. Since there are usually some stakeholders who are more engaged in knowledge generation and others who are more concerned with knowledge application, a model can be laid out to guide research from knowledge generation to application and then through the cycle again and again.

This recognizes and promotes mutual learning. If done properly, it can benefit all stakeholders.

Reward Systems
In pursuing field research, with a multiplicity of stakeholders, one must keep in mind the difference in reward systems facing different stakeholders. Managers in industry and government are rewarded for accomplishments that benefit their immediate employees. The time horizon for such benefits often varies as a function of managerial level. Very often senior management will recognize a long-term payoff from research and will enter into an agreement with university researchers. They will then, however, pass responsibility for managing the relationship to middle level managers, who may have a very different agenda with a much shorter time horizon. On the other side of the transaction, university faculty have a vested interest in education and research producing

knowledge for educational purposes. While all faculty are motivated to publish, senior faculty, already guaranteed security through tenure can afford to assume a long-term perspective in this regard. Junior faculty, facing an eventual tenure review, need to get their publication out to the academic community more rapidly. This, coupled with the fact that engineering systems research is only gradually becoming recognized as a legitimate subject (There are no recognized journals yet), makes it very risky for junior faculty to engage in engineering systems research.

(The paper will expand on these and other related topic areas)

Lean Enterprises

Deborah J. Nightingale

Introduction

Lean enterprises are increasingly important in achieving critical strategic goals such as responsiveness, cycle time and cost across all phases of the product life cycle. The Lean Aerospace Initiative defines a lean enterprise as:

> *A lean enterprise is an integrated entity that efficiently creates value for its multiple stakeholders by employing lean principles and practices.*

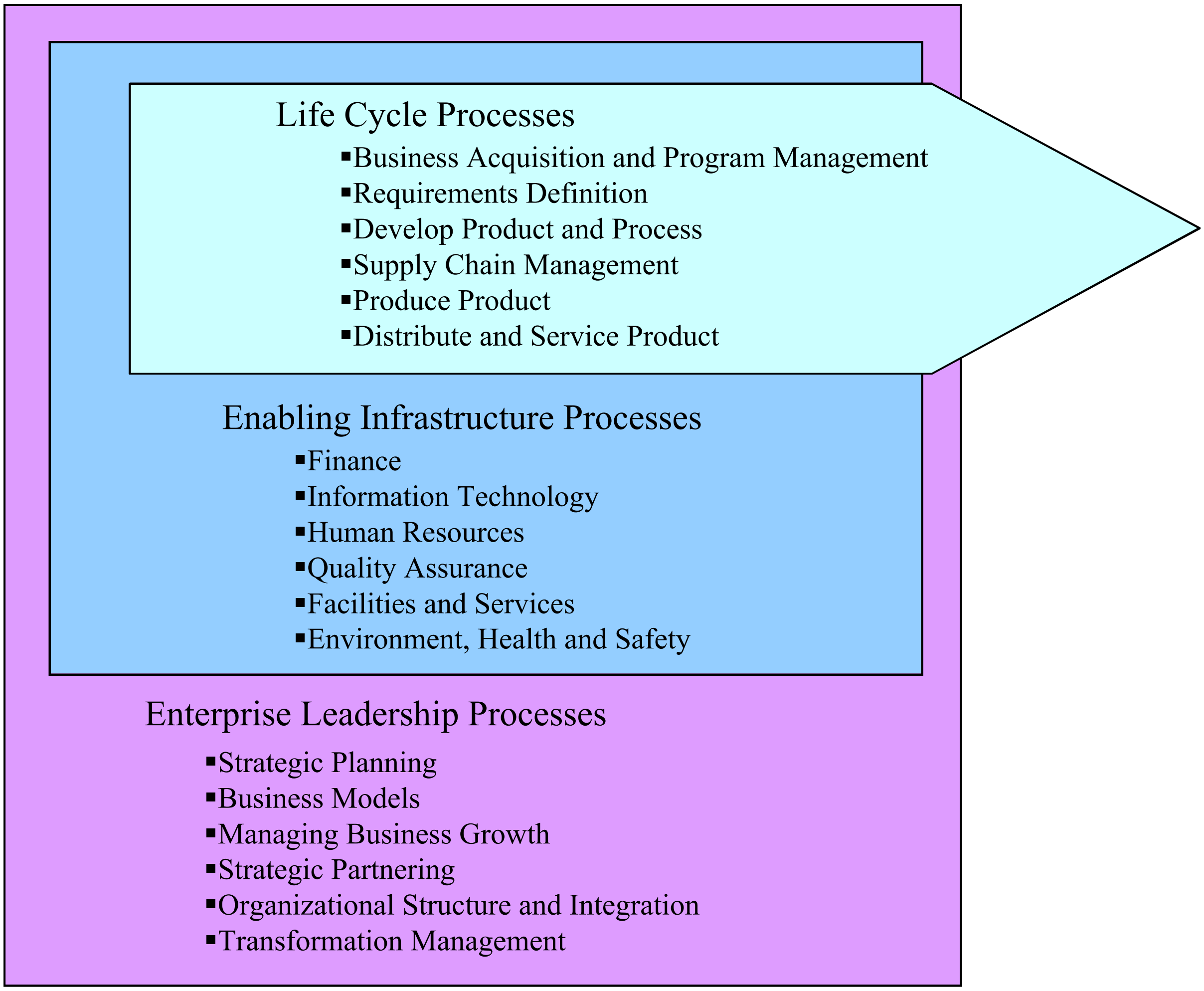
Lean enterprises systematically employ lean thinking and as such are dynamic, knowledge-driven and customer focused — consistent with the definition of lean thinking. As a result, they are responsive to change. A lean enterprise is continuously evolving with its environment, seeking improvement and perfection. The full benefits of lean can be realized only by re-thinking the entire enterprise: its structure, policies, procedures, processes, management practices, reward systems, and external relationships with customers and suppliers.

Enterprise Architecture

What are the enterprise processes in a corporation, business unit, or government agency that need to be transformed in order for it to be a lean enterprise? A generic lean enterprise architecture is used as the organizing framework, as shown in Figure 1. The architecture is organized into three basic groups, each consisting of a number of enterprise level processes. All of these processes must be transformed in order to achieve a lean enterprise.

Figure 1

Generic Lean Enterprise Process Architecture



Life Cycle Processes: These processes define the product life cycle, from initial conception through operational support and ultimate disposal. These are the value stream activities that contribute directly to the creation of products, systems, or services delivered to the enterprise's customers. These processes reflect the lean view of an overall product lifecycle within which functions serve, as opposed to the more traditional paradigm that allows each function to suboptimize around its own operations.

Enabling Infrastructure Processes: These support the execution of Enterprise Leadership and Life Cycle processes. The enabling processes provide supporting services to other organizational units whom they serve as internal customers. Since they enable rather than directly result in enterprise success, they can be easily overlooked as sources of waste within the value stream. In a lean enterprise, though, they are reoriented to support the 'Lifecycle Processes'. This can involve a major transformation in the operation of most support functions.

Enterprise Leadership Processes: These processes are developed and maintained by leadership to guide the activities of the enterprise. They cut across all of the entities that make up the enterprise. Enterprise leadership provides the direction and resources to break down barriers among and within Life Cycle Processes that result in wasted resources and reduced value to customers and stakeholders. They also provide the leadership to transform the Enabling Processes to eliminate waste and improve responsiveness to the rest of the enterprise.

Enterprises are comprised of processes, people/organizations, information, and enabling technologies. To create value efficiently, these various elements of an enterprise must be appropriately linked and integrated. All portions of the organization (including life cycle as well as enabling processes such as Finance, IT, and HR) must operate in fundamentally different ways in the lean environment than they did under the mass paradigm.

In general, there are three aspects involved in transforming the above processes to "lean:"

1. First, the mission, procedures, practices, processes, and metrics of each organizational unit must be re-created, consistent with the requirements of a lean business model.
2. Second, the fundamental principles of lean behavior (waste elimination, balanced flow, etc.) must be implemented within a framework of on-going continuous improvement.
3. Third, the enterprise must be integrated across all the important dimensions: organizations, information, processes, and enabling infrastructures.

Enterprise Stakeholders
Additionally, in any complex enterprise there are multiple stakeholders. These stakeholders may include customers, partners, suppliers, shareholders, employees, and society. While lean principles were initially focused heavily on the customer, more recent enterprise research has revealed that the critical success factor for today's enterprises is to *balance* the needs of *all* stakeholders. This leads to new challenges and complexity for enterprise leadership.

Leadership
Transforming an entire enterprise to lean has revealed new challenges in the role of leadership in effecting a change of this magnitude. Issues such as multi-program process standardization, global seamless information flow, and enterprise-level optimization across multiple stakeholder objectives are critical strategic factors. Leadership commitment and alignment is critical to becoming a lean enterprise. Most critical are the overall enterprise leaders, who drive lean practices and principles from the top of the organization. Enterprise change management and assessment methodologies have been developed to assist leaders in lean transformation.

Engineering System Issues

Enterprises must be viewed holistically, with the above issues addressed as a complex integrated system. Enterprises do ***not*** lend themselves to the traditional decomposition approach to complex systems. Just as product development cannot be effectively accomplished without the extensive involvement of other life cycle processes such as manufacturing, supply chain, and the customer, so too must all three sections of the enterprise architecture be included in enterprise transformation and analysis. Leadership and Enabling processes, in particular organizational and information infrastructure issues, must all be considered in parallel and in an integrated fashion – thus adding to the complexity of the enterprise as an engineered system.

New methodologies, analysis approaches, and research on these complex system interrelationships are required.

The Concept of a "Clios Representation" illustrated by the Mexico City case

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Complex, large-scale, integrated, open systems (CLIOS) are a class of systems of special interest in the Engineering Systems Division.

A system is *complex* when it is composed of a group of related units (subsystems), for which the degree and nature of the relationships is imperfectly known. Its overall behavior is difficult to predict, even when subsystem behavior is readily predictable. Further, the time-scales of various subsystems may be very different.

CLIOS have impacts that are *large* in magnitude, and often *long-lived* and of *large-scale* geographical extent.

Subsystems within CLIOS are *integrated*, closely coupled through feedback loops.

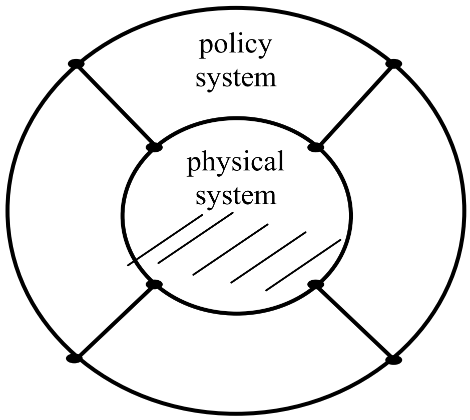
By "*open*" we mean that CLIOS explicitly include social, political and economic aspects.

Often CLIOS are counterintuitive in their behavior. At the least, developing models that will predict their performance can be very difficult to do. Often the performance measures for CLIOS are difficult to define and, perhaps, even difficult to agree about, depending upon your viewpoint. In CLIOS there is often human agency involved.

"Representing" a system as a CLIOS, diagrammatically and with text, can be a useful mechanism for understanding its underlying structure and behavior. This paper defines the concept of a "CLIOS representation", and then considers the Mexico City metropolitan area transportation/environmental system as an illustration of how a CLIOS representation can be utilized in practice.

The motivation for a CLIOS representation is "nested complexity". The physical manifestation of Mexico City is a CLIOS in and of itself. Nested complexity occurs when the physical CLIOS is being "managed" by a complex organizational and policymaking CLIOS, as is clearly the case in Mexico City.

Nested Complexity



CLIOS Representation

A CLIOS representation is a tool for capturing the key characteristics of a system in an organized systematic manner, so as to help the analyst avoid the omission of salient factors in both its physical manifestation and its organizational/institutional manifestation.

We make an explicit distinction between the physical system and institutional/organizational system,* but also explicitly represent the connection between the physical and institutional/organizational system, so as to understand the sources of nested complexity.

This is largely a conceptual process -- we don't expect to get quantitative results from the CLIOS representation -- rather, we hope for insight.

* n.b. the institutional/organizational system is intended to capture the various stakeholders and their interests.

Steps in a CLIOS Representation

1. Overarching description of CLIOS identifying major characteristics/ issues

   e.g., geographic scale, network structure, political structure, demographics…..

   Embedded herein is usually problem identification

2. Identification of major subsystems and description of their key characteristics

3. Creation of the CLIOS diagram(s) -- N.B. We often need CLIOS diagrams at various scales to represent the full richness of a system, so or example an "environment" subsystem may be expanded into a fuller representation considering various emissions, sources,… Further, it may be convenient to draw CLIOS diagrams in a layered format (e.g., travelers and freight, physical system and institutional system). These diagrams contain subsystems and links showing the influences of subsystems upon one another.

4. Characterizing the nature of the links, including, for example

    Magnitude and direction of influence between subsystems
    Time frame of influence (immediate, long term…)
    Stochastic?
    Functional form (e.g., linear, nonlinear, threshold…)
    Adaptive
    Human agency
    Others usually associated with relations among organizations/institutions
        Hierarchical
        Command and control
        Advisory
        Info-sharing

5. Use the above results to "seek insight" about overall system behavior -- emergent behavior, considering, for example

    Interactions among multiple subsystems
    Fast-moving, high-influence interactions
    Strong positive feedback loops

Post-CLIOS Representation Steps

6. Identification of key performance measures

    Per Capita Increase

    Air Quality
    .
    .
    .

7. Identification of Policy/Strategic Options Intended to Improve System Performance. Relate these options to the subsystems identified earlier.

    "Think through" the systemic impact of these options -- which extends to quantitative analyses by various methods.

8. Option Evaluation and Selection
9. Implementation Strategy
10. Post-Implementation Evaluation and Modification

A CLIOS Representation of Mexico City

The paper then applies the process to Mexico City, focusing on the relationship between transportation, land use, economic development and environmental (particularly air quality issues).

Ideas on Complexity in Systems – 20 Views

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The term "complexity" is used in many different ways when applied to systems. The different uses of this term may depend upon the kind of system being characterized, or perhaps the disciplinary perspective being brought to bear.

The purpose of this paper is to gather and comment upon different views of complexity, as espoused by different authors, and to highlight similarities and differences among these perspectives. The purpose of the paper is not to make judgments among various complexity definitions, but rather to draw together the full richness of various intellectual perspectives about this concept, in order to understand better how complexity relates to the concept of engineering systems.

I have either quoted directly or done my best to properly paraphrase these ideas. I hope that this note will be useful as we begin to think through the field of engineering systems.

Sources

J. Morley English in **Economics of Engineering and Social Systems**; Complexity in internal management of a system (like the space program) vs. complexity in the objectives of a social system -- the space program had a simple objective -- a man on the moon and back safely by the end of the 1960s.

Complexity as per **Rechtin and Maier** in **"The Art of System Architecting"**, page 7, 8.

From **"Dealing with Complexity",** by **Flood and Carson,** after **Vemuri** in **"Modeling of Complex Systems", 1978, New York: Academic Press.**

Complex situations are often partly or wholly unobservable, that is, measurement is noisy or unachievable (e.g., any attempt may destroy the integrity of the system).

"**Frontiers of Complexity"** by **Coveney and Highfield:**

"Complexity is the study of the behavior of macroscopic collections of such units that they are endowed with the potential to evolve in time."

From **"The Economist", June 5, 1999,** an article entitled **"Complex Equations":**

The article discusses "complexity management" in the context of banks and insurers, referencing work by BAH.

From **"Consilience: The Unity of Knowledge"** by **Edward O. Wilson:**

Wilson discusses complexity theory, saying that "The greatest challenge today, not just in cell biology but in all of science is the accurate and complete description of complex systems."

From **"The Social Psychology of Organizations"** by **Katz and Kahn**:

They note that it is a big mistake to use biological metaphors to describe patterned human activity (Allport). "Social systems are more contrived and biological systems and have no dependable life cycle."

From **"Rescuing Prometheus"** by **Tom Hughes**:

"Social scientists and public intellectuals defined the baffling social complexity to which the systems approach enthusiasts believed they could respond as a problem involving indeterminacy, fragmentation, pluralism, contingency, ambivalence, and nonlinearity. Ecologists, molecular biologists, computer scientists and organizational theorists also found themselves in a world of complex systems. Humanists -- architects and literary critics among them -- see complexity as a defining characteristic of a postmodern industrial world."

From **"The Idea of Economic Complexity"** by **David Warsh** (Boston Globe columnist) -- his ideas on economic complexity suggests that it is fundamentally hierarchical. He does include some useful characterizations of the thinking of others, e.g.:

John Von Neumann -- Redundancy is a complex system's way of dealing with failure.

John H. Holland: Hidden Order: How Adaptation Builds Complexity -- Holland is from the Santa Fe school of complexity. This book captures much useful thinking. He starts with "basic elements": agents, meta-agents and adaptation and the idea of 'cas', which stands for complex adaptive systems. His metaphor is evolutionary biology although his examples are more broadly drawn, such as a large city -- indeed, that is his first example. He defines 4 properties -- aggregation, nonlinearity, flows and diversity and 3 mechanisms -- tagging internal models and building blocks. He develops the idea of adaptive agents, rules and emergence and finally a software model called 'echo' based on sites, resources and strings which he uses on some simple cases to show how organization emerges.

David Levy, UMASS/Boston, has several papers **"Applications and Limitations of Complexity Theory in Organizational Theory and Strategy"** to appear in "Handbook of Strategic Management", and **"Chaos Theory and Strategy: Theory, Application,**

Management Implications", Strategic Management Journal, Vol. 15 (1994). I quote from the former:

"Comparing Chaos and Complexity Theory"

Both chaos and complexity theory attempt to reconcile the essential unpredictability of non-linear dynamic systems with a sense of underlying order and structure. There are, however, some significant differences between the two approaches. Chaos theory searches for a small number of deterministic mathematical functions driving a system; in population models, for example, these functions might represent the fluctuations in the numbers of a species. Network theory is less concerned with underlying simplicity; it tends to rely on brute computing power to model large numbers of nodes connected by simple logical rules. Network theory is more interested in the emergent order and patterns in complex systems rather than trying to find a simple mathematical engine in the system. Network models often try to capture the essence of interaction among the many agents in a system while chaos theory generally attempts to model some resultant outcome, such as prices or investment."

A. O. Hirschman and C. E. Lindblom, Economic Development, Research and Development, Policy Making: Some Converging Views, *Behavioral Science*, vol. 7 (1962), pp. 211-22.

The authors consider the three fields of interest noted in the title, each of which can be characterized as a *complex* system in the social-political-economic realm. They essentially argue that in each of these areas (drawing on the work of others), that unbalanced growth, apparently irrational strategies like duplication of resources and "confusion" and lack of communication may in fact be effective strategies in this context. Lindblom (in his earlier work) argues that there is a fallacy in thinking that "public policy questions can best be solved by attempting to understand them" and that there is almost never "sufficient agreement to provide adequate criteria for choosing among possible alternative policies". He goes on to discuss what he calls "disjointed incrementalism", where no attempt at comprehensiveness is made in policy-making. He argues that comprehensive policy-making in complex systems will always fail because of value conflicts, information inadequacies and general complexity beyond man's intellectual capacities.

W. Brian Arthur, On the Evolution of Complexity -- a chapter in <u>Complexity</u> by Cowens, Pines and Meltzer (eds.).

Arthur speaks about three ways in which systems become more complex as they evolve.

First, he discusses "ecosystems" (which may be organizational as well as biological in nature) in which individuals find niches within a complex web to fill. He uses the pre- and post-automobile transportation industry as an example. In the pre- period, buggy whip factories, etc., exploited niches; then the auto was invented and this quickly simplified the system, only to see it become more complex over time. He notes that, "In evolving systems, bursts of simplicity often cut through growing complexity and establish new bases upon which complexity can then grow." He cites Newton simplifying greatly the approach of Ptolemy, the latter based on a geocentric model of the solar system with tremendous complexity introduced to make it "work". Newton, with a few laws, developed the simple ideas which govern the solar-centric model and which had greatly superior predictive power.

Second, Arthur discusses "structural deepening", noting that to enhance performance, subsystems are added. This refers to individuals (not ecosystems) becoming more complex. The original design of the gas-turbine had one moving part. Then to enhance performance, complexity -- subsystems -- were added.

Third, he discusses complexity and evolution through "capturing software" like electricity or the mathematics of derivative trading on the financial market.

Murray Gell-Mann, Complex Adaptive Systems -- book chapter in <u>Complexity</u> by Cowens, Pines and Meltzer (eds.).

In an article on complex adaptive systems (CAS), Gell-Mann discusses the CAS cycle.

"When we ask general questions bout the properties of CAS, as opposed to questions about specific subject matter such as computer science, immunology, economics, or policy matters, a useful way to proceed, in my opinion, is to refer to the parts of the CAS cycle.

I. coarse graining,

II. identification of perceived regularities,

III. compression into a schema,

IV. variation of schemata,

V. application of schemata to the real world,

VI. consequences in the real world exerting selection pressures that affect the competition among schemata, as well as four other sets of issues:

VII. comparisons of time and space scales,

VIII. inclusion of CAS in other CAS,

IX. the special case of humans in the loop (directed evolution, artificial selection), and

X. the special case of composite CAS consisting of many CAS"

Charles Perrow, Normal Accidents: Living with High-Risk Technologies

Perrow argues that our systems have become so complex and closely coupled that accidents are "normal" and cannot be assured against. He discusses the idea of components being joined by complex interactions, so that the failure of one affects many others. One idea of his is a "common-mode" component being used for several purposes (e.g., a pump) so that when it fails, a number of difficult-to-predict interactions occur. Further, these components are tightly coupled, so that failures propagate though the system quickly (and perhaps not visibly).

He uses the word "linear" to contrast with "complex" when he describes interactions among subsystems (or components). By linear he means interactions occur in an expected sequence. By complex he means they occur in an unexpected sequence.

John Sterman, in his book **Business Dynamics**:

His underlying world view is system dynamics, emphasizing the "multi-loop, multi-state, nonlinear character of the feedback systems in which we live". He says that "natural and human systems have a high degree of dynamic complexity". He emphasizes that complexity is not caused simply "by the number of components in a system or the number of combinations one must consider in making a decision". The latter is combinatorial complexity, finding the optimal solution from a very, very large number of possibilities.

Stuart Kauffman, At Home in the Universe: The Search for the Laws of Self-Organization and Complexity.

Kauffman is of the Santa Fe School. His framework is biology, primarily. He thinks that Darwin's chance and gradualism cannot have been enough of a theory of evolution to get us where we are today. He writes about self-organizing systems as the additional and necessary piece of the puzzle.

Complexity as per **Joel Moses** in his memo **"Complexity and Flexibility"**, which uses node and link structures.

Detail complexity vs. dynamic complexity as per **Peter Senge** in **"The Fifth Discipline"**, page 71.

Complexity as in CLIOS (**Joseph Sussman, "The New Transportation Faculty: The Evolution to Engineering Systems",** *Transportation Quarterly*, Summer 1999 and ***Introduction to Transportation Systems*****,** Artech House Publishers, Boston, 2000.)

The final paper will relate and contrast these various approaches.

Comparison of Information-Processing and Power-Processing Systems Based on Physical Laws and Constraints Applied to Design Methods and System Architecture

Daniel Whitney

It is widely agreed that the design methods and computer support of VLSI design are generally more mature than those of mechanical items. Why is this so, and is there any hope of the gap being significantly closed? This paper argues that there are fundamental reasons, that is, reasons based on natural phenomena, that keep mechanical design from approaching the ideal of VLSI design methods. Profound differences in the architectures of VLSI systems and mechanical systems can be explained in a similar way.

The essence of the argument is that VLSI and similar systems process information using minute amounts of power that are incidental to the information processing function. Mechanical systems like aircraft engines and cars process power itself, in large amounts, and are consequently subject to many constraints. VLSI systems can afford to support huge mismatches in impedance between sources and loads, while mechanical systems must match impedances. This virtually eliminates back-loading in VLSI systems. Thus they can consist of standard load elements that can be designed independently of possible applications in systems, while mechanical components and systems must be designed together. VLSI systems are more easily made modular as a result, while mechanical systems must be more integral.

Over the last 40 years, nearly every mechanical device whose real function was to process information at low power, such as calculators, clocks, and multi-dial numerical displays, has been replaced by much faster, cheaper, and more accurate electronic versions. The new versions are highly integral internally but are easy use as modules in highly interchangeable ways. As a result, a whole technology has arisen around the plug and play principle. It is exploited in electronic components, stereo systems, computer systems and peripherals, and many other applications. Interface standards have been defined to assist this exploitation, including designs of electrical plugs, voltage levels, assignment of certain pins on the plug to certain functions, and so on. In many ways, one can say that the existence of standard interfaces is the main enabler of modularity in many industries. Why is it that this trend has not been extended to mechanical items that carry or operate at high power? Why are typical high power or high stress things like airplane wings integral?

I argue that the amount of power or the local power density (power concentrated in a given volume) involved in delivering the product's functions severely limits a designer's choices regarding its modularity. High power items like car engines and aircraft wings need to economize on space, weight, and energy consumption while at the same time delivering multiple functions. Modular designs would not do. They would have too many parts, be too big, or weigh too much. Their interfaces are subjected to considerable physical or thermal stress as part of the item's main function. If the interfaces were independent spatially from the item and designed independently to standards, they would be too big or weigh too much.

Information handling products operate at vanishingly small power levels. An important reason why they are easier to modularize than power-handling products is that their interfaces can be standardized. Products like microprocessors exchange and process information, which is expressed as low power electrical signals. Only the logical level of these signals is important for the product's function. The interfaces are much bigger than they need to be to carry such small amounts of power. For example, the conducting pins on electrical connectors that link disk drives to motherboards are subjected to more loads during plugging and unplugging than during normal operation. Their size, shape, and strength are much larger than needed to carry out their main function of transferring information. This excess shape can be standardized for interchangeability without compromising the main function. This is why different kinds of disk drives can be used by one computer manufacturer in many models of computer. The information itself can also be standardized, with the result that different disk drives (to continue the example) can be substituted functionally as well as physically with few incompatibilities.

Power-handling items cannot easily be functionally substituted because power exchanges between them will not be efficient unless their power delivery and consumption characteristics are coordinated. This is called impedance matching. Information-handling items exchange so little power that impedance matching is unnecessary. The interfaces of power-handling items carry such large loads that there is little design slack left over to divert to interface standardization.

In a typical low power system, the main functions are carried out by standard items whose behavior and design rules have been determined and verified ahead of time. Because these items do not load each other, they can be combined in practically unlimited ways without their behavior being modified. Design effort and verification can then focus on systemic behavior. By contrast, the main functions of a high power system are carried out by purpose-designed items, and standard pre-verified parts are low or no function things like screws. Each part has to be independently verified and then the combination must be verified because the parts load each other and their behavior in the system is different from their behavior as independent items. Thus module design and system design are intertwined in scope and time.

To conquer the inherent complexity of low power systems, engineers exploit the modularity to build up systems layer by verified layer. Independence and simplicity of function of these modules are the reason why such systems are designable at all. Far fewer engineering hours are needed to design a 10 million part microprocessor than a 2 million part airplane. To achieve efficiency, designers of high power systems exploit the multi-functionality of the parts. Such systems are thus harder to design and verify, but integrality is not regarded as a fatal barrier. Attempts to design such systems modularly can result in kludges. They appear as hilarious examples in Design for Assembly texts.

It is debatable whether microprocessors carry out a single function, and the large power densities in microprocessors cause their internal elements to interact strongly, making their design difficult to modularize. Nevertheless, the majority of information-handling items do one or a very few functions that can be clearly separated from each other internally and externally. Designers of these items have considerable freedom to add or subtract functions. This freedom is not often available in power-handling products because the higher power levels bring with them side effects like vibration, crack growth, and heat radiation that cannot be avoided. More design effort typically goes into predicting and mitigating these side effects than goes into determining how to deliver the main functions. Obviously, side effects cannot be standardized, and this is another reason why power-handling items cannot easily be substituted functionally.

In summary, modularity in low power systems is enabled because

- The modules do not back-load each other
- They can therefore be designed and verified independently of how or where they will be used
- Their interfaces carry low power or stress
- Economy of scale exists for their manufacture
- Interfaces do not deliver a main function or affect performance, do not consume major design resources like space, and can be defined and designed independently of the items they join

On the other hand, integrality in high power systems is either mandated or exploited when

- The modules back-load each other
- Modules and the systems they constitute must therefore be designed together
- Interfaces consume valuable resources and must be tailored to each application
- High power creates side-effects that cannot be controlled separately from control of main functions
- Integrality presents opportunities to consolidate functions

Defining Engineering Systems: Investigating National Missile Defense (NMD)

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The MIT Engineering Systems Division is currently building its intellectual framework. There is not yet consensus within ESD as to which tools and methods are central to the nascent engineering systems approach; which questions it should address; or the extent to which qualitative approaches should be incorporated into it. The goal of this paper is to sharpen the debate by presenting multiple analyses of a single engineering system. Presenting varying perspectives would illuminate issues such as:

- What types of questions should engineering systems practitioners ask when analyzing problems?
- Which tools are fundamental, which are peripheral, and which lie outside its purview?
- Is there a trade-off between the analytical rigor of different tools and the degree to which they can address questions the approach considers important?

I propose using the national missile defense (NMD) concept as a vehicle for this investigation. NMD is heavily based on technical artifacts; it requires a complex infrastructure to be deployed successfully; and it incorporates political and other qualitative components in addition to its technical design. Moreover, the complexity of NMD facilitates the framing of analyses on multiple levels, and provides a vehicle for exploring the ramifications of different potential definitions of "engineering systems."

Paper Outline

I propose taking three cuts at the NMD problem:

- Technical description with probabilistic exercise
- Engineering systems tools: system thinking/CLIOS; game theory, systems analysis
- Relationship between Congressional appropriation and military procurement procedures and system architecture

A. Technology/Probability

The analysis will begin with a brief description of the technical elements of the system (radars, interceptors, command-and-control) and of several potential architectures of the system. A brief probabilistic analysis showing how successful different potential architectures (midcourse, boost-phase) might be in intercepting potential attacks will show the system's capabilities and the degree of confidence policy-makers might have in preventing/deterring ballistic missile attacks on the United States. The data from the probabilistic analysis will also be used in the second section of the paper.

B. CLIOS/System Thinking

Initial CLIOS analysis has identified several characteristics of the NMD system. First, missile defenses themselves heavily integrated in the CLIOS sense, as there are several examples of feedback between subsystems that might lead to nonlinear behavior or even true emergent behavior (with the tracking radar and interceptors' guidance systems one example). Second, there is also coupling between US defense spending and nuclear posture and other countries' spending and choices to build ballistic missiles – feedback that may be both positive and negative. The CLIOS analysis suggests that the U.S. should couple the decision to build a missile defense with other programs designed to reduce feedback; possibilities include a more robust testing program and renewed emphasis on non-proliferation and strategic arms limitations.

C. Game Theory

An alternative to representing NMD as a CLIOS or using system dynamics would be to represent it as a game or set of games. Unlike CLIOS, game theory introduces choice explicitly into the representation of the system. At the same time, game theory does not capture the interactions and feedback as neatly. A game-theoretic analysis illuminates the differing responses of potentially unfriendly nations to a U.S. decision to proceed with a missile defense.

D. Systems Analysis

A third engineering systems approach is to illustrate potential trade-offs between potential goals of an NMD system (size of attack, likelihood of intercept, geographic coverage of the system) and system designs, with their attendant costs and potential failure modes. The analysis explores several proposed system architectures, and uses available technical and cost analyses to estimate the incremental performance and costs of more complex NMD designs.

E. Likely Research and Appropriations Decisions

The final look would focus on how Congress and the military purchase weapons, and project how appropriations policies would interact with any missile defense system design. This view would be the inverse of the traditional engineering systems approach. Rather than starting with a set of goals and examining which combinations of technologies meet those goals at minimum cost, it instead starts with how the system might be purchased and where it might be deployed, with the technology and the goals of the system appearing as constraints in a qualitative analysis. I hypothesize that the military and the Congress are likely to purchase a broader range of interceptors than what the technical analysis would suggest, and to purchase fewer supporting systems (early warning radars, testing). Individual segments of the system may be less reliable and effective, but the system on the whole is likely to be at least as effective. It is also likely to be considerably more costly.

Fundamental Principles for Engineering Systems

This work suggests some simple engineering systems principles, including:

- No single analysis method is sufficient to describe a system; using multiple perspectives simultaneously can deepen insights
- Organizational realities deflect systems away from “optimal” performance to allow other goals to be met